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Outdoor Thermal Comfort of Residents in a Warm Humid Climate

A study on informal settlements in Dar es Salaam, Tanzania

Modest Maurus Baruti

THESIS

13

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- Assisted self-help housing as a tool for resource mobilization and community cohesion

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Doctoral Thesis

Keywords

Outdoor thermal comfort, microclimate, thermal perception, urbanites, informal settlements, informal urban fabric, warm humid climate, Dar es Salaam, Physiological Equivalent temperature (PET), New Standard Effective Temperature (SET*), Universal Thermal Climate Index (UTCI)

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Dedication

To my family and closest friends, Eugenia and Evelyn Baruti, for all their love, encouragement, patience, and support.

Abstract

In the informal settlements of warm humid climates, where the majority of urbanites spend most of their time outdoors, a conducive thermal environment is crucial for their social and economic well-being. The overall aim of this thesis is to increase knowledge and understanding of outdoor thermal comfort in informal settlements in the warm and humid climate of Dar es Salaam, Tanzania. Urbanites' thermal perception and coping strategies during different seasons (wet and dry) were investigated using micrometeorological measurements and structured questionnaires. Spatial and temporal variations of outdoor thermal comfort and various measures (vegetation and building height) to improve thermal comfort were investigated using a simulation model (ENVI-met 4.4.3). Two informal settlements, Kawe located near the coast of the Indian Ocean and Tandale located 5 km inland, were selected. Thermal comfort was estimated using three different thermal indices (PET, SET* and UTCI).

The comfort range in informal settlements is shown to be narrower and higher than in formal areas, and the lack of adaptive options causes poorer thermal conditions for the urbanites. Higher comfort ranges indicate higher adaptive capability of the urbanites and reveals their tolerance of higher index temperatures. The study noted marginal variations in maximum air temperature between seasons, but thermal comfort relief in the dry (cool) season is linked to the substantial decrease in air humidity. Incremental increase of building height in a street canyon to 12, 18, and 24 m reduces PET by 2.5, 2.8, and 3.8°C respectively at 14:00. Similarly, varying leaf area index by 2, 4, and 6 m^2/m^2 leads to a reduction of the T_{mrt} by 7.9, 10.1, and 12.2°C, and PET was reduced by 3.9, 4.7, and 5.6°C respectively at 14:00, which emphasises that shade from trees is an effective measure to reduce heat in the tropics. The study reinforces the necessity to upgrade informal settlements and employ climate-sensitive urban design, integrating the influence of microclimate and thermal comfort. Further studies to investigate the effect of climate change on the microclimate and on urbanites' thermal perception in informal settlements of warm humid climates is recommended.

Contents

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To God be the glory.

List of articles and author's contribution

Paper I – Review of studies on outdoor thermal comfort in warm humid climates: challenges of informal urban fabric
Baruti, M. M., Johansson, E. & Åstrand, J. (2019). Review of studies on outdoor thermal comfort in warm humid climates: challenges of informal urban fabric. Int J Biometeorol, 63, 1449–1462.

The author conducted a systematic search of literature on the subject in collaboration with Assoc. Prof. Johansson. The author designed the structure of the article, analysed the content of the literature, and substantiated the knowledge gap. He also wrote initial drafts in collaboration with Assoc. Prof. Johansson and Åstrand, who reviewed and commented on the manuscript.

Paper II – Urbanites' thermal perception in informal settlements of warm-humid Dar es Salaam, Tanzania
Baruti, M. M. & Johansson, E. (2020). Urbanites' thermal perception in informal settlements of warm-humid Dar es Salaam, Tanzania. Urban Climate, 31, 100564

The author coordinated and conducted micrometeorological measurements and a survey campaign in Dar es Salaam, Tanzania between March and July 2017. He processed and analysed data from both micrometeorological measurements and the survey, and carried out a microclimate and thermal comfort investigation with guidance from Assoc. Prof. Johansson. The author wrote the initial drafts and created the data visualisations, and Assoc. Prof. Johansson reviewed and commented on the manuscript.

Paper III – Urbanites' thermal comfort in the informal urban fabric of warm-humid Dar es Salaam, Tanzania.

Baruti, M. M., Johansson, E. & Yahia, M. W. (2020). Urbanites' thermal comfort in informal urban fabric of warm-humid Dar es Salaam, Tanzania. Sustainable Cities and Society, 62, 102380.

The author designed and planned the structure of the article. He was responsible for analysis of data for microclimate and thermal comfort, prepared the initial drafts, and created data visualisations. Assoc. Prof. Johansson and Dr. Yahia provided critical feedback, which helped to shape the research, analysis, and the manuscript.

Paper IV – Spatial and temporal variability of microclimate and outdoor thermal comfort – focus on the informal urban fabric in warm-humid Dar es Salaam

Baruti, M. M, Johansson, E. & Yahia, M. W. (Manuscript). Spatial variability of microclimate and outdoor thermal comfort in informal urban fabric of warm-humid Dar es Salaam, Tanzania.

The author conducted the measurements in the modelled area (Tandale), imported the modelled area into the ENVI-met 4 software using open street maps and ENVI-met Monde, and calibrated the results in collaboration with Assoc. Prof. Johansson and Dr. Yahia. The author conducted simulations of microclimate and thermal comfort, analysed the results, created data visualisations, prepared the structure of the article, and wrote initial drafts of the manuscript. Assoc. Prof. Johansson and Dr. Yahia reviewed the manuscript and provided critical feedback, which shaped the analysis and the manuscript.

List of acronyms

AT	Apparent Temperature
ARU	Ardhi University
ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
clo	Clothing value
D	Diffuse short-wave radiation
DI	Discomfort Index
ET*	New Effective Temperature
HDM	Housing Development and Management
H/W	The ratio of building height (H) and street width (W)
ITCZ	Inter Tropical Convergence Zone
$L\downarrow$	Long-wave radiation from the sky
L_{st}	Long-wave radiation from street surface
L_w	Long-wave radiation from wall surface
LAD	Leaf Area Density
LAI	Leaf Area Index
MEMI	Munich Energy Balance Model for Individuals
met	Metabolic rate
MTPV	Mean Thermal Perception Vote
PET	Physiological Equivalent Temperature
PMV	Predicted Mean Vote
PT	Perceived Temperature
R	Reflected short-wave radiation
RBL	Rural Boundary Layer
RH	Relative Humidity
S	Direct short-wave radiation
SET*	New Standard Effective Temperature
Sida	Swedish International Development Cooperation Agency
SVF	Sky View Factor
T_a	Air Temperature
T_g	Globe Temperature
T_{mrt}	Mean Radiant Temperature
T_{sk}	Mean Skin Temperature

THI	Temperature Humidity Index
TOP	Operative Temperature
TPV	Thermal Perception Vote
UBL	Urban Boundary Layer
UCL	Urban Canopy Layer
UHI	Urban Heat Island
UTCI	Universal Thermal Climate Index
VP	Vapour Pressure
W	Wind
WBGT	Wet Bulb Globe Temperature

1 Introduction

1.1 Background

The world is experiencing a rapid growth in urban population, increasing from a yearly average of 57 million between 1990 and 2000 to 77 million between 2010 and 2015 (UN-Habitat, 2016). Africa's urban population growth rates have been the highest, above four per cent per year in the period 1950-1990, and are expected to remain at or above three per cent per annum through 2030 and 2035 (UN, 2015b). The rapid urban growth is reflected by the increase in the size and population of cities, as well as the resulting socio-economic developments (Wang et al., 2015). The emergence of informal settlements, which dominate the image of many cities in developing nations, is one of the effects of rapid urbanisation (Wekesa et al., 2011). In 2014, 881 million urban dwellers in the world lived in poor informal settlements as a result of rapid urbanisation, an increase from 689 million in 1990 (UN-Habitat, 2015).

Informal settlements are urban areas that develop and grow without formal planning, and in which basic facilities are mostly lacking (Mkalawa, 2016). The term 'informal' refers to the settlements that are usually built without legal tenure and without following established building and planning regulations (Abbott, 2002). According to Augustijn-Beckers et al. (2011), the major reasons for the growth of informal settlements are the weaknesses of statutory planning and a strong rural–urban migration. Hofmann et al. (2008) define informal settlements as (i) areas where groups of housing units have been constructed on land that the occupants have no legal claim to or occupy illegally, and (ii) areas where housing is not in compliance with the current planning and building regulations (unauthorised housing). In Dar es Salaam[1], Tanzania, it has been observed that over 80% of all buildings are located in informal settlements (Kironde, 2006; Younga and Flackea, 2010). Kombe and Kreibich (2000) observed that the settlements are characterised by dwellings that are located haphazardly, rarely in conformity

[1] Commercial capital and the largest city of Tanzania in East Africa.

with ventilation needs. This, in turn, has consequences for microclimate and outdoor thermal comfort.

The urban fabric[2] greatly affects the urban climate, as built-up areas directly influence the microclimate in an urban environment (Eliasson and Svensson, 2002). The authors noted that the form and physical characteristics of built-up areas directly affect microclimate and outdoor thermal comfort. Climate-related environmental problems in tropical urban agglomerations include poor dispersion of air pollutants (generally low wind speed), a high level of heat stress which decreases productivity, reduced human thermal comfort, increased mortality due to heat related illness, and space cooling needs that increase energy usage, which in turn may exacerbate climate change (Roth, 2007). It is argued that improved urban designs that optimise thermal comfort can raise the quality of life in general, as well as help urban dwellers to cope with the episodes of hot weather and allow year-long outdoor activities (Kalkstein and Valimont, 1986). In addition, if the outdoor climate is thermally comfortable, urban space use levels are more likely to increase (Nikolopoulou and Steemers, 2003).

Several studies (Morakinyo et al., 2017; Morakinyo et al., 2018; Yahia et al., 2018) have shown that the use of vegetation, especially trees with medium to high leaf area index (LAI[3]), considerably improves both microclimate and outdoor thermal comfort in street canyons in different climates. It is worth noting that the growth of informal settlements in Dar es Salaam is associated with a loss of green spaces (Roy et al., 2018). Subsequently, analysis of the association between ambient temperature and morbidity/mortality noted that urbanites[4] who live in less vegetated areas have a higher risk of morbidity/mortality compared to those living in more vegetated areas (Schinasi et al., 2018). It is well known that trees play a big role in modifying the microclimate and improving the thermal environment of the urbanites; however, there is a need to quantify the effectiveness of spatial distribution and foliage density in informal areas.

[2] Urban fabric reflects the morphological composition of physical elements within a certain area, which can be represented/defined by indicators such as density, compactness, variation, fragment, and cohesion (Li et al. 2016). Fabric refers to the natural and construction materials that form urban elements such as buildings, roads, and vegetation. It determines the radiative, thermal and moisture properties of a surface and its abilities to absorb, reflect and emit radiation, and to accept, transfer and retain heat and water (Oke et al. 2017).

[3] LAI is a dimensionless variable and is defined as one-half the total double-sided leaf area per unit of ground surface area (Duarte et al., 2015).

[4] A person who lives in a town or city.

Sustainable Development Goal 11 of the United Nations 2030 Agenda emphasises the importance of making cities and human settlements inclusive, safe, resilient, and sustainable (UN, 2015a). Urban planning and design plays a great role in the wellbeing of urbanites in terms of environmental effect and overall thermal experience.

1.2 Problem statement

A number of studies have investigated the influence of settlements on microclimate and outdoor thermal comfort of urbanites in warm humid tropical and subtropical climates (Baruti et al., 2019). However, most of these studies focused on the formal urban fabric of cities (e.g. squares, parks, train stations, leisure areas, beaches, and semi-outdoor spaces), which differs from the informal urban fabric. In the urban context, studies have reported microclimate and outdoor thermal comfort differences between low-rise and high-rise building areas (Johansson and Emmanuel, 2006; Johansson et al., 2013; Rodríguez Algeciras et al., 2016; Sharmin et al., 2015; Yahia et al., 2018). Yahia et al. (2018) noted that low-rise, dense, informal urban fabric areas in Dar es Salaam have higher mean radiant temperatures (T_{mrt}[5]) than formal urban areas, posing thermal discomfort challenges in the informal areas.

Urbanites in informal settlements are facing challenges of increased thermal discomfort conditions due to rapid urbanisation and global warming (Johansson, 2006). As noted by Rose (2011), in developing countries, outdoor discomfort conditions affect largely the urban poor who spend much of their time outdoors and have no alternative means to deal with the heat. The city of Dar es Salaam hosts about 9.5% of the country's population, estimated at 54 million in 2018, and continues to attract the majority of migrants. Dar es Salaam was one of the top three fastest growing cities in all of Africa and the tenth globally in this category in 2010 (Peter and Yang, 2019). It can be postulated that lack of control of the formation of the urban fabric in the informal settlements largely jeopardises the thermal comfort of urbanites.

For decades, the research community investigating informal settlements has focused on social, economic, and environmental challenges, but thermal comfort issues have not been given adequate attention (Baruti et al., 2019; Ramsay et al., 2021). Currently, only a few studies

[5] The uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body equals the radiant heat transfer in the actual non-uniform enclosure (ASHRAE 2001).

(Kakon et al., 2009; Sharmin et al., 2015; Yahia et al., 2018) have compared the formal and informal urban fabrics in terms of microclimate and outdoor thermal comfort. None of the mentioned studies have investigated urbanites' subjective perception of outdoor thermal comfort in the informal urban fabric. Little is known about the influence of the informal urban fabric on the microclimate and on the urbanites' thermal comfort and perception. Studies should examine urbanites' outdoor thermal perception in the informal urban fabric of warm humid climates as well as tacit knowledge of urbanites' coping strategies, such as change of clothes, drinking (cold or ambient temperature beverages), and walking habits (shaded areas or use of parasol). Addressing these areas will not only deepen our knowledge of thermal comfort but also accelerate key items of policy implications regarding the improvement of informal settlements.

1.3 Aim and research questions

The overall aim of this thesis is to increase knowledge and understanding of outdoor thermal comfort in informal settlements in the warm and humid climate of Dar es Salaam, Tanzania. The specific aims are to analyse urbanites' thermal perception and coping strategies during different seasons, to map spatial and temporal variations of outdoor thermal comfort, and to evaluate different measures to improve the outdoor thermal comfort. The thesis intends to answer the following research questions.

RQ1 How do urbanites in the informal settlements in the wet and dry seasons perceive the outdoor thermal environment?

RQ2 What are the thermal comfort ranges, thermal neutrality, and thermal preference for urbanites in the informal urban fabric of Dar es Salaam for the wet and dry seasons?

RQ3 What is the extent and variation in terms of application of different coping strategies by urbanites in the wet and dry seasons?

RQ4 How do urban design measures, such as addition of trees with different leaf area index and incremental increase of building heights, influence outdoor microclimate and outdoor thermal comfort in informal settlements?

1.4 Research limitations

This study had the following limitations:

(i) The geographical context was limited to the city of Dar es Salaam and two neighbourhoods: Kawe and Tandale (see Chapter 4);

(ii) The micrometeorological measurements and questionnaire survey focused on the public spaces of the main streets of Kawe and Tandale during the warmest part of the day, 11:00-16:00, in both wet (March) and dry season (July);

(iii) The simulations were limited to the informal settlement of Tandale.

1.5 Structure of the thesis

This thesis is a compilation thesis, consisting of two major parts – a summarising section and four appended papers. The summary is made up of eight chapters. The first chapter presents the background, problem statement, aim, research questions, and limitations of the study. The second chapter presents the conceptual framework of the study and discusses the main concepts, their components, and practical implications. The third chapter presents information on the urban development of the study region and its climate, including a brief description of Dar es Salaam and an elaboration on its urban development. The fourth chapter presents the research methods used in this study, their design and approach, the fifth summarises the most important findings of the study, and the sixth presents a discussion of the results. The seventh chapter presents conclusions and recommendations, including implications of the study for practitioners and policy makers, and the eighth presents areas for further research.

The appended papers are structured and divided into four parts. Paper I starts by substantiating a knowledge gap through a systematic review of outdoor thermal comfort studies in warm humid climates. Papers II and III are based on a combined analysis of micrometeorological measurements and survey questionnaires. In particular, Paper II investigates urbanites' thermal perception and their coping strategies, while Paper III investigates outdoor thermal comfort limits and the influence of microclimate on urbanites' thermal perception. Paper IV evaluates spatial and temporal variability of the microclimate and outdoor thermal comfort in informal areas through microclimate simulations.

1.6 Outline of the research

Figure 1.1 presents the hierarchy of the study, and shows the links between the research aims, research questions, embedded concepts, methods, and final output. The major research aims generated four main research questions, which gave rise to concepts that later formed the conceptual framework.

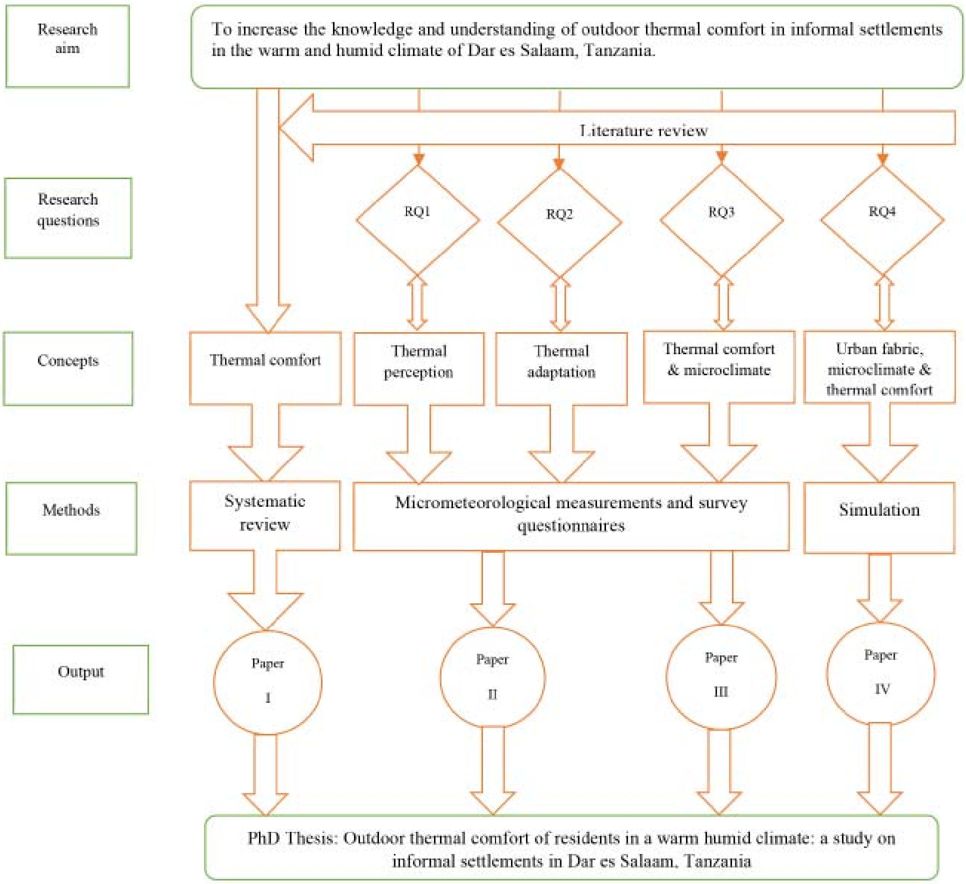


Figure 1.1 A schematic diagram showing the process of various stages of the study linking research aim, research questions, embedded concepts, methods, and final output.

2 Conceptual framework

In this chapter a general description of the concepts outdoor thermal comfort, urban microclimate, and urban fabric is presented, and how they are interlinked, including their components. A summary of findings from previous thermal comfort studies in warm humid climates and practical implication is provided.

To understand and explore the phenomena, a conceptual framework must be built up. As Jabareen states:

> *Conceptual framework is a network, or "a plane" of interlinked concepts that together provide a comprehensive understanding of a phenomenon or phenomena. The concepts that constitute a conceptual framework support one another, articulate their respective phenomena, and establish a framework-specific philosophy (Jabareen, 2009, p. 51) .*

According to Miles and Huberman (1994, p. 18), a conceptual framework is a visual or written product, one that "explains, either graphically or in narrative form, the main things to be studied such as the key factors, concepts, or variables and the presumed relationships among them". The subject of outdoor thermal comfort is multi-disciplinary, integrating concepts from various fields, e.g. urban climatology, urban design, urban planning, biometeorology, physiology, and environmental psychology. It is worth noting that "reviewing the literature leads to a delineation of the conceptual or theoretical framework of the study" (Berger and Patchener, 1988). Focused research questions enable the formulation of appropriate concepts for the study (Bouma, 1993).

2.1 Outdoor thermal comfort

Thermal comfort can be defined as "that condition of mind which expresses satisfaction with the thermal environment"(ASHRAE, 1966, 2004; ISO-7730, 1984), or absence of thermal discomfort, that is to say, that an individual feels neither too warm nor too cold (McIntyre, 1980). Fanger (1970) describes thermal comfort as a state when heat flows to and from the human body are in equilibrium. Thermal comfort is evaluated on the basis of an individual's thermal perception, which refers to conscious interpretation and elaboration of sensory data (Knez et al., 2009). Thermal perception is subjective, implying that not all people will experience comfort in the same environment. Thermal comfort zones are typically thought to satisfy 80% of people (de Dear and Fountain, 1994).

2.1.1 Factors affecting thermal comfort

Factors affecting thermal comfort can be grouped as follows: environmental, personal and situational (Knez et al., 2009). Environmental factors include air temperature (T_a)[6], T_{mrt}, air humidity and wind speed. Personal factors include biological base (metabolic rate, activity), demographic variables (age and gender), and psychological parameters (knowledge/experience, attitudes/expectations, preferences, perceived control). Situational factors include length of exposure (physiological adaptation) and clothing (thermal insulation, evaporative resistance).

The tropical warm humid savannah climate/ tropical wet/dry climate (Aw) (e.g. Dar es Salaam) is characterised by moderately high T_a and high air humidity throughout the year, with minimal diurnal variations (Kottek et al., 2006). Solar radiation is high, which means that a person is exposed to high short-wave radiation and long-wave radiation from the heated surfaces (Johansson, 2016), resulting in a high T_{mrt}. The magnitude of T_{mrt} is strongly linked to the sky conditions; on clear days, T_{mrt} may be twice as high compared to cloudy/overcast days (Johansson, 2016). A combination of high T_a, Tmrt and air humidity in this climate creates a thermally uncomfortable environment, as high levels of humidity restrict evaporative cooling from the body. Similarly, a high humidity level increases discomfort due to the feeling of moisture in the skin and increases friction between the skin and the clothes worn (ASHRAE, 2001). In warm humid climates, air movement is necessary for thermal comfort of a person, as it facilitates convective heat loss from the skin.

Heat production of the human body is directly proportional to the level of activity (metabolic rate). In the tropics, a high activity level has

[6] Air temperature is the temperature of the air surrounding an individual and is typically measured in degrees Celsius (°C) or degrees Fahrenheit (°F) (Wilson and Corlett, 2005).

negative consequences on the thermal comfort of a person, as heat loss from the body is restricted (Johansson, 2016). Clothing with high clo values (high thermal resistance) restricts heat loss from the body and leads to thermally uncomfortable conditions. Similarly, age and gender can influence the way a person perceives the thermal environment, as women tend (not statistically significant) to have a preference for slightly higher temperature levels than their male counterparts (Wang et al., 2018). Personal psychological factors, i.e., knowledge/experience, attitudes/expectations, preferences, and perceived control, also affect thermal perception (Nikolopoulou and Steemers, 2003). Length of exposure (physiological adaptation) is one of the important factors, as the thermal perception of the environment influences people's decision on how long to spend in the area (Nikolopoulou and Lykoudis, 2006; Nikolopoulou and Steemers, 2003).

2.1.2 Indoor to outdoor thermal comfort

Theories of thermal comfort from early studies such as Fanger (1970), Gagge et al. (1967) and Givoni (1963) on indoor thermal comfort were later adapted to outdoor thermal comfort studies (Nikolopoulou et al., 2001; Nikolopoulou and Lykoudis, 2006; Pickup and de Dear, 2000b; Potter and de Dear, 2000; Spagnolo and de Dear, 2003). Fanger (1970) defined three parameters for a person to be in thermal comfort: a) the body is in heat balance; b) the sweat rate is within comfort limits; and c) the mean skin temperature is within comfort limits. These conceptual requisites can be expressed in measurable terms, such as body-core temperature within a very narrow range, 36.5-37.5°C, a skin temperature of 30°C at the extremities and 34-35°C at body stem and head. At these temperatures, the body will be free of sweating (Epstein and Moran, 2006).

Fanger (1970) developed the first approach, which was based on the heat balance model of a human body (the classic steady-state model for air-conditioned spaces). Fanger's model aims to predict the mean thermal perception of a group of people and their respective percentage of dissatisfaction with the thermal environment, expressed through the indices Predicted Mean Vote and Predicted Percentage Dissatisfied (PMV–PPD) (Rupp et al., 2015). PMV is calculated through four environmental variables, T_a, T_{mrt}, air velocity, and air humidity, and two personal variables, metabolism and clothing.

Later, a second approach to determine thermal comfort (the adaptive model) was developed, based on the adaptive principle (Nicol et al., 2012). The adaptive model states that, "If a change occurs such as to produce discomfort, people react in ways that tend to restore their comfort." People are therefore active and not passive (as in the PMV method) in terms of their reactions to their thermal environment. The model was developed through field studies (de Dear et al., 1997; de Dear and Brager, 1998; Nicol and Humphreys, 1973, 2002) in naturally ventilated buildings in different climates. The adaptive model is based on three interrelated aspects: psychological (comfort expectation and habituation in relation to indoor and outdoor climate), behavioural, and physiological (acclimatisation) (de Dear et al., 1997). According to Rupp et al. (2015), the concept of alliesthesia proposed by Cabanac (1971) and revisited by de Dear (2009) was used to define the physiological and the behavioural aspects of the adaptive method (thermal pleasure). According to Cabanac (1971), "a given external stimulus can be perceived either as pleasant or unpleasant depending upon signals coming from inside the body." People naturally attempt to avoid unpleasant stimuli and search for pleasant ones (Cabanac, 1971).

2.1.3 Outdoor thermal comfort challenges

Outdoor and semi-outdoor spaces present challenges, as the microclimatic variables are dynamic. In outdoor thermal environments, people are directly exposed to local microclimate conditions of solar radiation, shading, and changes in wind direction and speed (Chen and Ng, 2012). The thermal comfort range in the outdoor environment is therefore wider than indoors, ranging from a state of thermal comfort to a stressful environment (Spagnolo and de Dear, 2003). Outdoor conditions show large temporal and spatial variations, and the thermal balance of the body is seldom in a steady state, unlike in a controlled indoor environment (Johansson, 2006; Johansson et al., 2018; Nikolopoulou et al., 2001).

Another notable challenge presented by the outdoor environment is the tools for assessing outdoor thermal comfort. Despite the common use of Fanger's PMV-PPD model in evaluating thermal comfort in outdoor environments, its use outdoors led to considerable discrepancies between the actual perception vote, collected subjectively through questionnaires of thermal comfort, and the PMV (Chen and Ng, 2012). In addition, determination of thermal comfort in the outdoor environment has to include the influence of solar radiation, which is included when calculating the effects of T_{mrt}. Consequently, several thermal indices, which will be discussed later, have been developed for the assessment of the outdoor environment.

2.1.4 The physiological approach

Fanger (1970) noted that "man's thermoregulatory system is quite effective and will therefore create heat balance within wide limits of the environmental variables, even if comfort does not exist." However, the conditions for thermal comfort are narrow and highly dependent on mean skin temperature (T_{sk}) and sweat rate, which are dependent on the activity level. In addition, these definitions and limits put forth by Fanger (1970) can be applied only under steady state conditions (Höppe, 2002).

Unlike indoor thermal conditions, outdoor thermal conditions are dynamic and complex, with the major energy transfer being convective heat loss, evaporative heat loss, conductive heat loss, radiative exchanges, and metabolic heat production within the body (Brown and Gillespie, 1986). The physical factors affect the exchange of heat through the skin surface, which is the most important organ in human thermoregulation (Höppe, 2002) and consequently plays a large role in the human thermal physiological state (Sakoi et al., 2007). As a result, Fanger's (1970) definition of thermal comfort, which is based on the balanced heat budget at a comfort level of skin temperature and sweat rate, can only be used in steady state conditions (Höppe, 2002).

The application of the thermal indices developed on the basis of the steady state energy balance models of the human body face a similar challenge when it comes to the outdoor thermal environment. Their application is confined to situations when people stay outdoors for a long time (Höppe, 2002). Noting all these developments and challenges they address, Nikolopoulou states:

> *It is apparent that we now have a range of tools evaluating outdoor thermal comfort at varying degree of sophistication, simulating anatomical, thermal and physiological properties of the human body. However, in this process we have distanced humans and the real world context. The same way that studies in climate chambers distance people from real buildings, which led to the debate between conventional and adaptive thermal comfort conditions and eventually led to an adaptive comfort standard, we are facing similar if not wider divergence in the outdoor context (Nikolopoulou, 2011, p. 1554).*

The necessity to look beyond thermal physiology in examining outdoor thermal comfort is to incorporate both thermal physiology and field studies as a way of triangulating the outcome of the study. This follows the observation of researchers who found that thermal indices alone cannot adequately describe the thermal conditions of a person (Johansson et al., 2018; Knez and Thorsson, 2006; Knez and Thorsson, 2008; Krüger et al., 2017). It is likely that culture and environmental attitude influence thermal perception, hence the need to link thermal comfort indices to the emotional perception of the environment (Knez and Thorsson, 2008). Krüger et al. (2017) argue that the direct application of thermal comfort indices might prove to be inappropriate if psychological processes involved in environmental assessments are not accounted for. This observation corresponds with Lin et al. (2011), who argued that thermal indices cannot fully predict thermal comfort conditions outdoors but they can serve as indicators.

2.1.5 Field study approach

Unlike other scholars' works on outdoor thermal comfort that focus on theoretical thermoregulatory models, field questionnaire surveys on outdoor thermal comfort call for an understanding of the subjective human parameter, to evaluate outdoor thermal comfort more holistically. Field studies to investigate outdoor thermal comfort have been conducted in different places in warm humid climates, such as Dhaka, Bangladesh (Ahmed, 2003), Hong Kong (Cheng et al., 2010), Dar es Salaam (Ndetto and Matzarakis, 2016), and Taiwan (Lin, 2009). These studies focused on evaluating the relationship between outdoor thermal comfort and environmental variables in different climatic contexts. As Nikolopoulou pointed out:

> *As it would be expected, the influence of different climatic parameters varies according to climatic contexts, but all the studies highlighted the complexity in determining the relationships between environmental variables and thermal comfort. Furthermore, a common finding from all the surveys concerned the wide range of comfort zones experienced; significantly wider than would be defined by theoretical models, strengthening the argument for thermal adaptation (Nikolopoulou, 2011, p. 1555).*

Field studies involve micrometeorological measurements, including the four basic environmental variables with an influence on thermal comfort, namely ambient temperature, air humidity, wind speed, and T_{mrt}, which is usually calculated. The measurements are conducted in parallel with questionnaire surveys, which include questions on two behavioural variables: activity that connotes metabolic rate and clothing that connotes clothing insulation. The notable difference of the field study approach when compared to other approaches is that respondents provide responses in their everyday environments, wearing their everyday clothing, and behaving without restrictions.

2.1.6 Thermal adaptation

The term 'adaptation' can be broadly defined as the gradual decrease of the organism's response to repeated exposure to a stimulus, involving all the actions that make them better suited to survive in such an environment (Nikolopoulou and Steemers, 2003). This involves a process through which people go to improve their thermal comfort as they respond/adapt to their environment. Adaptive behaviours are divided into three different categories: physical/behavioural, physiological, and psychological (Nikolopoulou, 2011).

Physical adaptation involves all the changes a person makes to adjust to the environment, or alter the environment to their needs; the adaptation can be active or reactive (Nikolopoulou et al., 1999). According to those authors, reactive adaptation involves changes at a personal level, such as altering clothing levels, posture and position, or even changing metabolic heat through consumption of hot or cool drinks. Interactive adaptation involves changes in the environment, such as opening windows, adjusting a thermostat, or opening a parasol. Physiological adaptation/acclimatisation implies changes in the physiological responses resulting from repeated exposure to a stimulus, gradually reducing the strain from such exposure (Nikolopoulou and Steemers, 2003). People's experiences, expectations of what the environment should be rather than what it is, length of exposure, perceived control, and environmental stimulation all influence their thermal perception of outdoor situations.

The consistent low correlations between objective meteorological variables and subjective thermal perception in field surveys across the world suggest that thermophysiology alone does not adequately describe these relationships; psychological factors also influence the thermal perception of a space (de Dear and Brager, 1998; Nikolopoulou, 2011). According to Nikolopoulou and Steemers (2003), psychological factors affecting thermal perception of a space include expectation, experience, perceived control, naturalness, environmental stimulation, and time of exposure. Expectations of what the environment should be like, rather than what it actually is, greatly influence people's thermal perceptions (Nikolopoulou and Steemers, 2003), and can be the major aspect for subjective assessment and satisfaction (Höppe, 2002). Nikolopoulou and Steemers (2003) associate expectation to the frequent responses people gave throughout a year, for example, "it is OK for this time of year", "for this time of year I would prefer it warmer", or "it's winter, it's meant to be cold."

In the same way, people's past experience also psychologically affects their assessment of the thermal environment (Nikolopoulou and Steemers, 2003). Experience can vary from short term (days) to long term (months to years). Long-term experience is related to the schemata people have constructed in their minds, determining a choice of action under different circumstances, such as changes in clothing, consumption of cool drinks to alter the metabolic heat, and moving from sun to shade (Nikolopoulou and Steemers, 2003). Short-term experience is related to the immediate past, as noted in some studies (Johansson et al., 2018; Ng and Cheng, 2012) in which respondents who were exposed to air-conditioning prior to the questionnaire survey were more tolerant of the heat stress. Similarly, factors such as length of exposure, perceived control and environmental stimulation have been observed to have a psychological influence on thermal perception of people (Nikolopoulou and Steemers, 2003).

2.1.7 Thermal comfort indices

Thermal comfort indices combine several factors (e.g. T_a, RH, wind speed, T_{mrt}, activity, clothing) into a single value, which sums up their simultaneous effects on the sensory and physiological responses of the body (Givoni, 1976). Indices are divided into two groups: simple indices, sometimes called empirical indices, and indices based on heat budget models, often called rational indices.

Simple indices

Simple indices represent the combined effect of two or more individual meteorological variables (T_a, wind speed, solar radiation, and air humidity) on humans. They can be based on empirical research or on theoretical considerations (Blazejczyk et al., 2012). One of the commonly used empirical indices developed for warm humid climates is the Discomfort Index (DI), also known as the Temperature-Humidity Index (THI) (Thom, 1959). It is represented by a linear equation quantifying the outdoor human comfort based on the T_a and air humidity (Coccolo et al., 2016). Other examples of simple indices are Apparent Temperature (AT)[7], Operative Temperature (TOP)[8] and Wet Bulb Globe Temperature (WBGT)[9].

Rational indices

Rational indices are based on the heat budget models of the human body, and take all mechanisms of heat exchange into account (Blazejczyk et al., 2012). Most rational indices (PMV, SET* and ET*) were developed for indoor applications (McIntyre, 1980). According to Spagnolo and de Dear (2003), applicability of PMV in conditions that vary greatly from neutrality, such as in outdoor conditions, is limited, as it was developed to describe thermal discomfort, not thermal stress. Nevertheless, the most commonly used indices in warm humid climates are Physiological Equivalent Temperature (PET)[10] (Matzarakis and Mayer, 1996) and new Standard Effective Temperature (SET* or OUT_SET*)[11] (Pickup and de Dear, 2000a; Binarti et al., 2020). Another common rational index is the Universal Thermal Climate Index (UTCI)[12] (Fiala et al., 2012).

Physiological Equivalent Temperature

The PET is defined as the T_a at which the energy balance for the assumed indoor condition (without wind and solar radiation) is in balance with the same mean skin temperature and sweat rate as calculated for the actual outdoor condition (Mayer and Höppe, 1987). PET is

7 The temperature at the reference humidity level producing the same amount of discomfort as that experienced under the current ambient temperature, humidity, and solar radiation.

8 This index is an arithmetic average of MRT and T_a, creating a single index.

9 An empirical heat stress index based on T_a, wet bulb temperature and globe temperature.

10 Thermal comfort Index, based on the energy balance equation of the human body, compares the actual outdoor conditions with the equivalent indoor conditions in order to evaluate the outdoor environment in terms of indoor standards.

11 Thermal Comfort Index, which represents the temperature of a standard environment at 50% relative humidity for subjects wearing clothing, standardised for the given activity in the real environment.

12 Universal Thermal Climate Index representing the T_a of a reference environment, which provides the same physiological response of a reference person as the actual environment.

based on the Munich Energy Balance Model for Individuals (MEMI) (Lawton et al., 1982), which models the thermal conditions of the human body in a physiologically relevant way (Höppe, 1999).

According to Mayer and Höppe (1987), the main idea of PET is to transfer the actual thermal conditions into an equivalent indoor thermal environment, in which the same thermal perception is expected. According to Höppe (1999), PET deliberately assumes constant values for clothing (clo = 0.9) and activity (80 W) in its calculation so as to define an index independent of individual behaviour. However, this does not essentially restrict its applicability, as the variation of clothing and activity – if varied equally outdoors and in the reference indoor climate – does not produce significantly different PET values. PET can be calculated using the PC application RayMan (Höppe, 1997; Matzarakis, 2002), which is developed based on Guideline 3787 of the German Engineering Society (Matzarakis, 2000).

The new Standard Effective Temperature

The SET* is developed from the new Effective Temperature (ET*) (Gagge et al., 1971). It is defined as the equivalent temperature of an isothermal, reference environment (RH = 50%, air velocity = 1.5 m/s, $T_a = T_{mrt}$), such that a person in the reference environment, wearing 0.6 clo and standing quietly with metabolic rate of 1.2 mets, has the same mean skin temperature (T_{sk}) and skin wettedness as the person in the actual complex environment (Gagge et al., 1986). The actual and reference environments are equivalent in terms of physiological strain and thermal discomfort because T_{sk} and skin wettedness are highly correlated with subjective discomfort in cool and warm environments respectively (Pickup and de Dear, 2000b). SET* uses T_{sk} and skin wettedness as the limiting conditions (Blazejczyk et al., 2012), and the values for T_{sk} and skin wettedness are derived from a two-node model of human physiology (Gagge et al., 1986; Gagge et al., 1971).

Universal Thermal Climate Index

The UTCI is based on the multi-node dynamic physiological UTCI-Fiala model (Fiala et al., 2012), which defines the thermal effects on the human body (for the whole body and individual parts) over a wide range of climates and validated with measured data. The UTCI-Fiala model divides the human organism into two interacting systems of thermoregulation: (1) the controlling active system that includes the thermoregulatory responses of shivering thermogenesis, sweat moisture excretion, and skin blood flow, and (2) the controlled passive system dealing with the physical human body and the heat transfer occurring in it and at its surface (Błażejczyk et al., 2010). The term multi-node describes the capacity of the model to predict local response of the human's body segments, with the human body divided into twelve cylindrical body elements: head, face, neck, shoulders, thorax, abdomen, upper and lower arms, hands, upper and lower legs, and feet (Fiala et al., 2012). Body elements are made of annular concentric tissue layers: brain, lung, bones, muscles, viscera, fat, and skin (Fiala et al., 1999), and are subdivided into a total of 63 spatial sectors. Clothing insulation is automatically calculated as a function of the actual T_a and wind speed, using an adaptive clothing model (Fiala et al., 2012).

Thermal perception scale

To evaluate subjective judgement of respondents on a given thermal environment, thermal comfort studies usually use a question on thermal perception of the type, "How do you feel right now?" followed by a subjective judgement scale. The commonly used scale is the 7-point scale often called the ASHRAE scale (ASHRAE, 1992; ISO-10551, 1995), subdivided as follows: cold (-3), cool (-2), slightly cool (-1), neutral (0), slightly warm (+1), warm (+2), hot (+3). Other studies use a 9-point scale (Fang et al., 2018; Johansson et al., 2018), adding very cold (- 4) and very hot (+4) (mainly for use in extreme environments) or a 5-point scale. In the latter case, the respondent's alternatives were normally very cold, cool, neutral, warm, and very hot. Thermal perception scales are directly linked to the thermal stress band for PET, SET* and UTCI as shown in Table 2.1.

Table 2.1 Original assessment scales of the Physiological Equivalent Temperature (PET) (Matzarakis and Mayer, 1996), the new Standard Effective Temperature (SET*)(McIntyre, 1980), and the Universal Thermal Climate Index (UTCI) (UTCI, 2017)

Scale	Thermal stress band	Thermal sensitivity	PET	SET*	UTCI
-5	Extreme cold stress				<-40
-4	Very strong cold stress	Very cold	<4		-40 to -27
-3	Strong cold stress	Cold	3-8	10.0-14.5	-27 to -13
-2	Moderate cold stress	Cool	8-13	14.5-17.5	-13 to 0
-1	Slight cold stress	Slightly cool	13-18	17.5-22.2	0 to 9
0	No thermal stress	Neutral	18-23	22.2-25.6	9-26
+1	Slight heat stress	Slightly warm	23-29	25.6-30.0	
+2	Moderate heat stress	Warm	29-35	30.0-34.5	26 to 32
+3	Strong heat stress	Hot	35-41	34.5-37.5	32 to 38
+4	Very strong heat stress	Very hot	>41	>37.5	38 to 46
+5	Extreme heat stress				>46

Thermal perception votes falling into the central categories (–1, slightly cool; 0, neutral; +1, slightly warm) of the thermal perception scale are considered as thermally acceptable votes (Lin, 2009; Spagnolo and de Dear, 2003).

2.2 Urban climate

Urban climate can be defined as an ensemble of the value of weather variables (i.e. T_a, humidity, wind speed, T_{mrt}) for a meteorological station located in an urban area, and includes an amalgam of background climate, topographic and human influences (Oke et al., 2017). Urban climate is a broad concept that encompasses several components at different scales. According to Givoni (1989), the climatic conditions in a man-made urban environment may differ appreciably from those in the surrounding natural or rural environment, as each urban man-made element – buildings, roads, parking areas, factories – creates around and above it a modified climate with which it interacts. Urban areas tend to be warmer and less windy (but gustier) than their surroundings. This warmth characteristic of the city noted between urban and surrounding rural areas temperature difference is known as the Urban Heat Island (UHI) (Oke et al., 2017). In Dar es Salaam, Kibassa (2014) noted that informal urbanisation has resulted in a UHI intensity of 1 to 3°C, more pronounced at night between 23:00 and 04:00.

2.2.1 Scales of urban climate

Understanding of the concept of urban microclimate requires a general knowledge of the scales of the urban climate. Airflow above the city creates different horizontal layers of air, each of which in turn creates its own climate (Oke, 1987). There are three identifiable spatial scales in urban areas: micro-, local, and meso-scales (Erell et al., 2011). These authors give a brief description of three scales of urban climate as follows:

> *Microscale* represents individual structures such as buildings, streets, gardens, trees, which cast shadows and redirect wind flow, and built elements such as balconies, which modifies reflection of sunlight, and the radiant temperatures to which people are directly exposed.

Local scale represents urban neighbourhoods and has a resolution of a single kilometre or less. It reflects man-made objects such as buildings, which in the context of a city or town makes up the urban fabric.

Mesoscale represents the entire city terrain in order of magnitude of tens of kilometres combining urban areas and their internal climatic effects. It also covers a broader magnitude of the urban and rural climatic influences.

2.2.2 The urban boundary layer

As air flows over a surface, the air layer adjacent to the surface (boundary layer) encounters the character of the surface below in terms of temperature, humidity, and roughness. The layer of air affected by the urban surface is called the urban boundary layer (UBL) (Figure 2.1) and can be divided into a number of different horizontal sub-layers: the

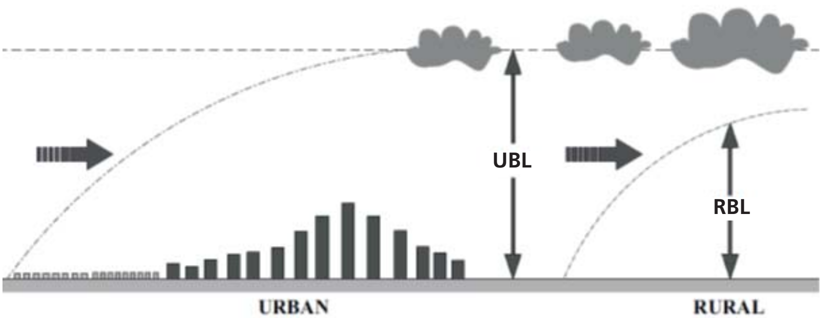


Figure 2.1 *Schematic section of the urban atmosphere showing urban boundary layer (UBL) and rural boundary layer (RBL). Source: Modified from Oke (1987)*

UBL is defined as the entire volume of air above the city that is influenced by its surface characteristics and by the activities within it (Erell et al., 2011). It usually extends upward ten times the height of the buildings, and its top can reach 1 km or more during the day but much less during the night (< 100 m). The UBL is usually deeper, less stable, warmer, and drier than the rural boundary layer (Oke et al., 2017).

UBL is influenced by the character of the city. In daytime, heating at the urban surface is stronger in most cities, creating entrenchment at the top of UBL, which makes it deeper than in rural areas (Oke et al., 2017). At the city scale, it is governed by mechanical and thermal convection due to industrial and other human activities. UBL is usually deeper, less stable, and drier than the rural boundary layer.

2.2.3 Urban canopy layer

UCL is the lowest part of the UBL (Figure 2.2). It extends upward to the height of buildings and trees and is governed by urban surface elements, i.e. buildings and trees, including their morphology, albedo, emissivity, and wetness. It is characterised by large temporal and spatial variations of T_a, air humidity and wind. As a result, the microclimate is site-specific and varies greatly within short distances (Arnfield, 2003; Johansson, 2006).

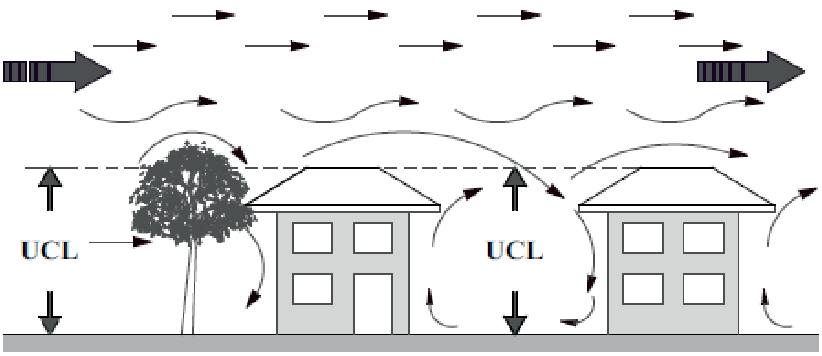


Figure 2.2 Schematic section of the urban canopy layer (UCL) extending from ground level to the height of buildings, trees, and other objects. Source: Modified from Oke (1987).

2.3 Determinants of the urban microclimate

Urban climate tends to differ from the surrounding (rural) climate due to a number of factors. These include the physical properties of the urban fabric and human activities (energy use and air pollution). In urban areas, street geometry affects radiation exchange (receipt/loss) and airflow, while the building fabric affects heat storage and waterproofing.

Similarly, vehicle traffic and space heating/cooling release anthropogenic heat. Closely spaced buildings lead to: (i) small sky view factor (SVF) (< 1), which reduces net longwave radiation loss (section 2.3.2), (ii) multiple reflections and greater shortwave radiation absorption (lower system albedo), and (iii) wind shelter in the UCL, which reduces heat losses by convection and advection (Oke, 1982, 1995; Oke et al., 1991). During the day, the urban canyon is a good absorber of solar energy and, because of the relatively high thermal capacity of urban surface materials, this energy is stored in the urban fabric and not released until after sunset (Nakamura and Oke, 1988).

2.3.1 Urban fabric

Urban fabric reflects the morphological composition of physical elements within a certain area, and can be represented/defined by indicators such as density, compactness, variation, fragment, and cohesion (Li et al., 2016b). According to these authors, the urban fabric can be understood by regarding the building as an 'object' and space as the 'background'. The plot, the street, the constructed space and the open space, also referred to as primary elements of the urban fabric, are used to identify and analyse the urban fabric (Levy, 1999). In order to analyse the influence of the urban fabric on the urban climate, there is a need to understand urban fabric descriptors at street level within the urban canopy layer. These include height-to-width (H/W) ratio, canyon axis orientation, and sky-view factor (SVF). Urban fabric descriptors form the basis of discussion and analysis of outdoor thermal comfort at urban level.

The geometry and materials that make up the canyons of a city greatly influence the urban climate (Arnfield, 1982; Oke, 1988). The geometry and orientation of the street canyon have also been shown to affect outdoor and indoor thermal environments, solar access inside and outside the buildings, the permeability to airflow for urban ventilation, and the potential for cooling of the whole urban system (Ali-Toudert and Mayer, 2006). In terms of outdoor thermal comfort, the street canyon is one of the most important elements of urban design. The street canyon influences thermal comfort at pedestrian level, as it directly affects the potential for airflow at street level, solar access, and therefore urban microclimate (Nakamura and Oke, 1988).

2.3.2 Height to Width (H/W) Ratio

The geometry of a street canyon is expressed by the ratio of the height of the buildings (H) to the width of the street (W), also referred as 'aspect ratio', and has a certain orientation in relation to the sun. For a non-symmetrical canyon, it is the ratio between the average height of adjacent vertical elements (building walls) and the average width of the space (i.e. the wall-to-wall distance across the street). Erell et al. (2011) propose that the average height and width allows for general categorisation in real-world streets, which are usually irregular.

The extent of the influence of the aspect ratio on the outdoor microclimate has been discussed in several studies (Emmanuel and Fernando, 2007; Emmanuel and Johansson, 2006; Ndetto and Matzarakis, 2013a; Sharmin et al., 2015; Yahia et al., 2018). Several studies in warm and humid climates (Emmanuel and Johansson, 2006; Sharmin et al., 2015) have shown that T_a decreases with increasing H/W ratio. Emmanuel and Johansson (2006) found that, in warm humid Colombo, Sri Lanka, the maximum T_a decreases with increasing H/W ratio more strongly on clear days and less so on cloudy days. The influence of H/W ratio on the microclimate was also noted in Dar es Salaam, where Ndetto and Matzarakis (2013b) found that both T_{mrt} and PET were reduced as building height increased. In warm and humid Colombo, Sri Lanka, Emmanuel et al. (2007) found that increased density (higher H/W ratios) can considerably reduce T_{mrt}.

2.3.3 Surface material properties

Other parameters such as properties of surface materials influence the climate in the urban canopy layer (Arnfield, 2003; Oke et al., 2017). One surface property is known as albedo, defined as the ratio of the incoming (shortwave) radiation reflected by a surface (reflectance) to the shortwave radiation reaching that surface (irradiance) (Oke et al., 2017). The amount of absorbed short-wave radiation from the sun depends on the colour of the surface (ground or wall) and urban geometry (H/W ratio). In urban areas, albedo values of surface materials can range from low (dark paint, tinted glass) or high (light paint, bright metals) (Oke et al., 2017). Conversely, the ability of surfaces to emit and absorb long-wave radiation is very similar for rural and urban surface materials whose emissivity lies at around 0.9 (Johansson, 2006).

A study by Aida (1982) found that, as the H/W ratio increases from 0 (a flat plane) to 2, the albedo of the system decreases from 0.4 to 0.23. In this case, the albedo of the system refers to the integrated effective albedo of the urban surface. Changing the albedo of urban surfaces through selection of materials or coatings can modify surface temperatures of walls and roofs and thereby modify the urban canopy layer microclimate. For example, a study by Yang et al. (2011), conducted in Shanghai, China, found that an increase of 0.4 in surface albedo lowered T_a at pedestrian level by 0.2-0.4°C but increased T_{mrt} by 8-14°C.

Another surface material property that influences the climate in the urban canopy layer is thermal admittance. Thermal admittance is the key parameter in determining how much of the radiation absorbed at the surface will be stored in the sub-surface. According to Runnalls and Oke (2000) thermal admittance is a surface property, defined as the square root of the product of heat capacity and thermal conductivity, that determines the rate of surface temperature change in response to heat gains or losses. The larger the thermal admittance, the smaller the surface temperature change for a given surface heat flux, and vice versa (Runnalls and Oke, 2000). Surface materials with lower thermal admittance (lawns, leaves) show greater fluctuations than surfaces with high thermal admittance (asphalt and bricks) (Christen et al., 2012).

2.3.4 Green areas and vegetation

Green areas dominated by grass and trees exert a great influence on the near-surface microclimate and thermal comfort of urbanites in the urban canopy layer. However, in urban areas, bare and vegetated soils are largely replaced by hard surfaces, e.g., pavements. As a result, the ground surface's ability to release energy through evaporation and transpiration is lost (Johansson, 2006). The extent to which the microclimate is influenced by trees varies with plant morphology (canopy form, foliage density, branch and root systems) and physiology, which depends on plant species, age and health (Oke et al., 2017). Trees or clusters of trees provide shade from solar radiation, including direct, diffuse, and reflected radiation (from walls and the street) and consequently lower T_a and, especially, T_{mrt} in the UCL. Apart from shade provided by trees, evapotranspiration[13] by plants contributes to the cooling of the surrounding air. Equally, trees modify the humidity in the air through photosynthesis, which exposes the moist interior of the leaf and permits

[13] Evapotranspiration is the water released to the atmosphere from the soil by evaporation and from the plants by transpiration.

evaporation (Oke et al., 2017). Relatively dry air passing through the tree canopy is thereby cooled. Trees also act as roughness elements, imposing a drag on air movement and making them effective wind shelters (Oke et al., 2017).

2.4 Microclimate and thermal comfort in a street canyon

In this section the climate of a street canyon with and without vegetation is described in terms of the meteorological variables (T_a, T_{mrt}, air humidity and wind) influencing the thermal comfort. Figure 2.3 shows a person in a street canyon exposed to solar radiation (above) and under the shade of a tree (below).

2.4.1 Air temperature

Air temperature (T_a) is the temperature of the air surrounding an individual, and is typically measured in degrees Celsius (°C) or degrees Fahrenheit (°F) (Wilson and Corlett, 2005). Within a street canyon (urban canopy layer), T_a is usually uniform except from within about 1 m from the canyon's surfaces (Nakamura and Oke, 1988). Surface material properties exert an influence on the magnitude and variation of T_a within a canyon. The reflectivity (albedo) of surfaces, which determine the amount of absorbed short-wave radiation, depends mainly on the colour of the surface, ranging from about 0.3 for light colours up to about 0.9 for dark colours (Johansson, 2006). In streets with trees or other types of vegetation T_a is lower (typically by 0.5-1.0°C) due to shading and evapotranspiration (Morakinyo et al., 2018).

2.4.2 Mean radiant temperature

Among the most important meteorological parameters governing the human energy balance and thermal comfort (heat load) is the T_{mrt} (Ali-Toudert and Mayer, 2007; Mayer and Höppe, 1987). In an exposed street canyon, a person receives short-wave radiation from the sun as direct (S), diffuse (D) and reflected (R) radiation, and long-wave radiation from surfaces such as building facades (L_w) and the ground surfaces (L_{st}) as well as from the sky ($L\downarrow$), which can be combined into T_{mrt} (Johansson, 2006) (Figure 2.3 above).

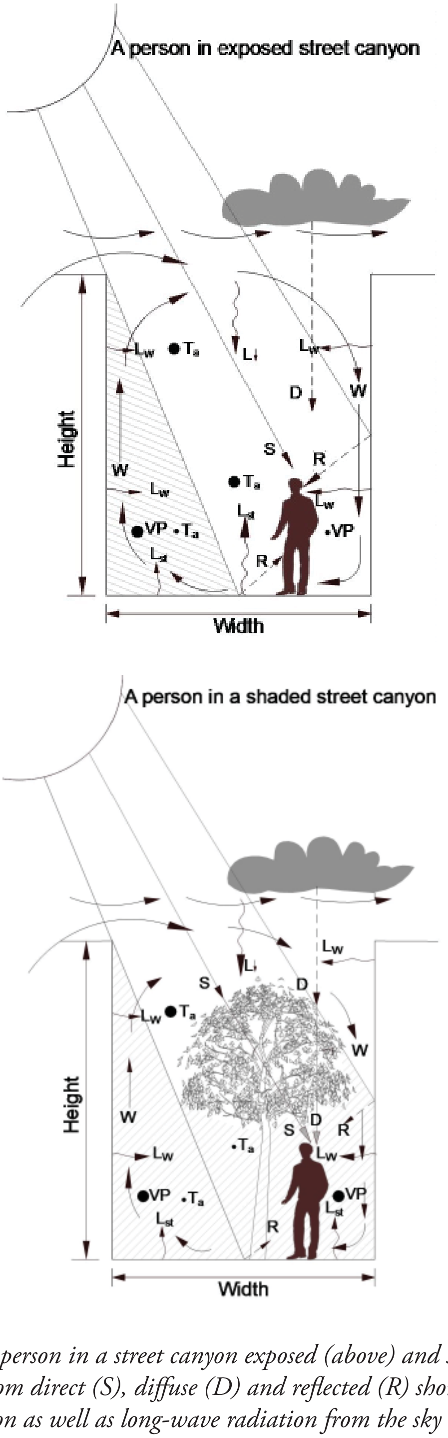


Figure 2.3 *A person in a street canyon exposed (above) and shaded (below) from direct (S), diffuse (D) and reflected (R) short-wave radiation as well as long-wave radiation from the sky (L↓) and urban surfaces (L_w and L_{st}). Effects of wind (W) and air humidity (VP) are considered. Source: Modified from Johansson (2006).*

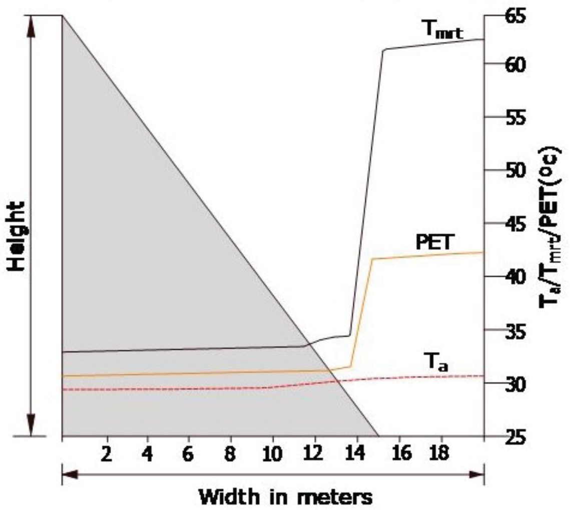


Figure 2.4 *A cross-section of a street canyon showing simulated variations of T_a, T_{mrt} and PET. Source: Modified from Oke et al. (2017), simulation by Nils Wallenberg.*

In the shaded part of the street canyon, incoming short-wave radiation (S) from the sky is substantially reduced, as it is either blocked by a wall (Figure 2.3 above) or a tree (Figure 2.3 below). As a result the radiation exchange between the person and the sky, urban surface, and objects such as trees consists mainly of long-wave radiation. According to Oke et al. (2017), a person receives direct beam irradiance and intercepts radiation emitted by warmer surfaces when moving from a shaded to a sunlit side (Figure 2.4). It is evident that, while the street canyon T_a differences are marginal during the day, the T_{mrt} shows large spatial variations over short distances, especially on the sunny side (Mayer et al., 2008; Thorsson et al., 2011). According to Thorsson et al. (2014), these variations are mainly determined by shadow patterns generated by 3-D objects (e.g. trees and buildings), and differences in thermal and radiative properties of the surrounding surface materials, i.e., albedo, emissivity, and heat capacity.

For outdoor environments, determination of T_{mrt} is complicated by multiple radiation from different sources (Figure 2.3). Nonetheless, the most accurate way to monitor T_{mrt} is by measuring short-wave and long-wave radiation flux densities from the 3-D surroundings of humans (east, west, north and south, upward and downward) and the calculation of angular factors (i.e. proportion of radiation received by the human body in each direction) (Thorsson et al., 2007). In a street canyon, T_{mrt} increases when crossing from the shaded to the sunlit side, and the PET index follows the path of T_{mrt} (Figure 2.4).

2.4.3 Air humidity

Air humidity is one of the important variables of thermal comfort. At high T_a, T_{mrt} and humidity, thermal discomfort prevails, since evaporative cooling is limited (Johansson, 2016). There are notable differences in humidity between shaded (with trees) and unshaded areas (Figure 2.3). This is because, under the tree, transpiration increases the amount of water vapour in the air and trees prevent the ground moisture from drying up by shading and through reduction of wind, which mixes the humid air and dry air above the tree.

2.4.4 Wind

The wind pattern in an urban canyon is affected by the geometry of the canyon and three-dimensional objects, e.g., trees. In a vegetated urban canyon, trees act as porous barriers that reduce mean wind velocity near the surface of the urban canyon, as shown in Figure 2.3 for wind directions perpendicular to the canyon axis. Acting as a porous barrier to the flow, the tree creates a small region of wind reduction on the windward side and lower speed on the leeward side (Takle, 2005). Wind direction varies greatly in an urban canyon with trees, as the wind is forced up from ground level.

3 Urban development and climate of Dar es Salaam

In this chapter, the historical overview of urban development of the city of Dar es Salaam from 1860 is discussed, and linked with the emergence and development of the informal settlements. In addition, the climate character of the city is presented.

Dar es Salaam, the commercial centre and largest city of Tanzania, is located along the coastal belt of the Indian Ocean at latitude 6° 53'S and longitude 39° 17'E. It covers an extensive area, 35 km north to south, and up to 30 km from east to west (Briggs, 2000). The city's roots date back to the 1860s, when Sultan Seyyid Majid bin Said from Zanzibar acquired a coastal strip of East Africa and established an administrative centre there (Sutton, 1970b). The name Dar es Salaam or 'Harbour or Haven of Peace' originates from the Persian Arabic word 'Bandar-ul-Salaam,' which was selected in 1862 (Kironde, 1994). The city was founded around the harbour and grew to occupy surrounding settlements and fishing villages along the coast, including the famous Mzizima, which was an open roadstead village directly facing the sea (Sutton, 1970a). Due to its rapid growth and its potential − a naturally sheltered harbour where large vessels could anchor safely − the German colonial government shifted the capital from Bagamoyo to Dar es Salaam in 1891 and established an administrative centre (Kironde, 1994; Nguluma, 2003). The urbanisation of Dar es Salaam is influenced by the colonial era and can be reviewed in two time periods: colonial (1887-1961) and post-colonial (1961-2002) (Abebe, 2011; Kironde, 1994; Sutton, 1970a).

3.1 Colonial urban development of Dar es Salaam

Dar es Salaam's colonial urban expansion was organised by the state and characterised by exceptional architectural edifices erected by imperial rulers who had confidence on the potential of the land (Brennan et al., 2007). The Germans built a road network radiating out from the harbour, along which the urban area grew. The monocentric radial development pattern consisted of four major arterial roads: Bagamoyo, Morogoro, Nyerere, and Kilwa, which characterised the spatial structure of Dar es Salaam (Nkurunziza, 2013). The city development experienced a steady population increase, with varying gross population density due to the extent of built-up areas in each period. As noted in Lupala:

> *Trends in the spatial growth of Dar es Salaam indicate that by the year 1891, the extent of the built up area of the city was limited to only 122 hectares of land and a gross population density of 45 persons per hectare. This figure increased to 463 hectares of land in 1945 and a gross density of 130 persons per hectare. The rapid expansion of the city took place between 1945 and 1963 when the built up area extended to 3081 hectares. This resulted into a sharp decrease in density to 49 persons per hectare (Lupala, 2002, p. 32).*

According to Kironde (1994), it was an acceptable colonial policy to demarcate plots, often with rudimentary or no services, on which natives could build in any materials. The aim was to relieve the colonial governments of needing to provide housing for the colonised populations. A typical example of those demarcated plots found in Dar es Salaam includes areas such as Kariakoo from the 1900s, Ilala in the 1930s, and Kinondoni, Magomeni, Temeke, and Mwananyamala in the 1950s and the early 1960s (Kironde, 1994). Gridiron layouts for African areas (Ilala, Kariakoo and later in Magomeni) were laid out, with plot sizes ranging from 250 to 300 square metres (Nguluma, 2003). The plot sizes played an influential role in the type of houses that were to be built in these areas, predominantly the Swahili type of house characterised by a central corridor with rooms on both sides (Vestbro, 1975). The British took over the city in 1920. The British colonial housing policy introduced a right of occupancy as a way of enforcing development control, which discouraged 'natives' from residing in the urban areas of Dar es Salaam (Nguluma, 2003). The right of occupancy was provided to Africans on a short- term basis to discourage them from building permanent structures (Kironde, 1994).

3.2 Post-colonial Dar es Salaam

After independence in 1961, most of the physical urban development, whether planned or unplanned, took place along the four major arterial routes (Abebe, 2011; Lupala, 2002; Mkalawa, 2016). Figure 3.1 shows Dar es Salaam's urban growth for the years 1963, 1978, 1992, and 2001, showing the four major arterial roads influencing the city's urban growth. According to Lupala (2002), until 1963 most of Dar es Salaam was 'planned' with the exception of a few informal settlements: Keko, Buguruni, Ubungo and Temeke. In addition, the city's built-up and consolidated areas was constrained within a 6-km radius. By 1978, the city's built-up areas had expanded to 14 kilometres along Pugu Road and around 12 kilometres along Morogoro and Bagamoyo Roads (Figure 3.1). Lupala (2002) also observed that, by 1992, the extent of the built-up area largely remained within the 12-km radius, but there was a notable extended development along Bagamoyo road up to 16 kilometres and 10 kilometres along Kilwa road. By 2001, the built-up area had begun to consolidate in previously sparsely developed areas between major roadways (Figure 3.1). Subsequently, the northern and western extension along Bagamoyo road and Morogoro road had reached about 32 and 28 kilometres respectively. The southern extension along Pugu and Kilwa roads had reached about 20 and 14 kilometres respectively.

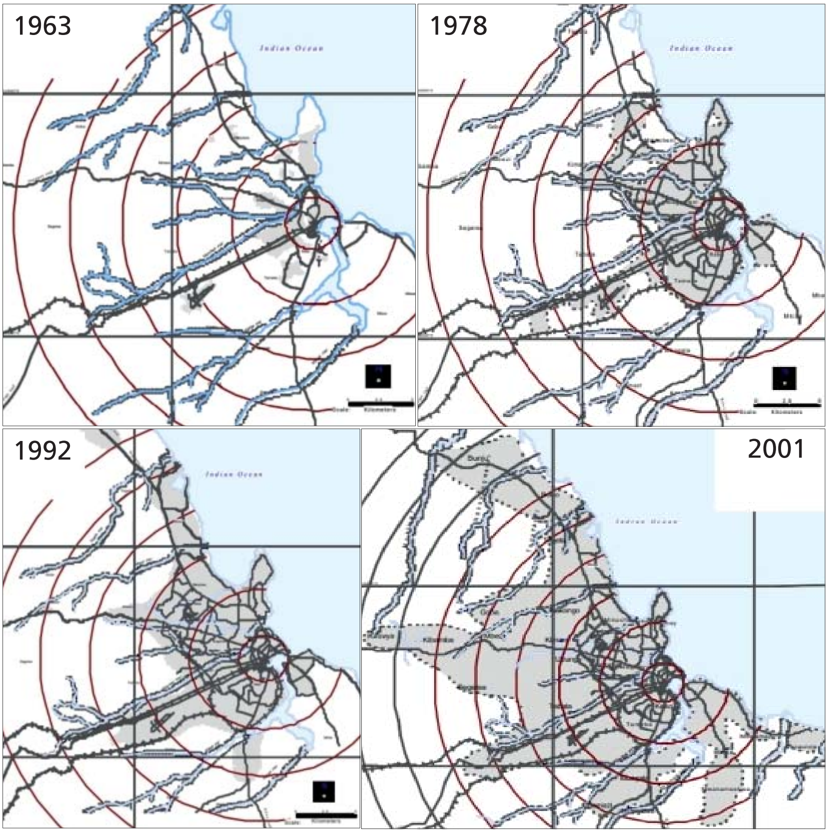


Figure 3.1 *Dar es Salaam's urban growth by 1963, 1978 1992, and 2001, characterised by urban growth along four arterial roads radiating out from the central business district (CBD). Source: (Kironde, 1994; Lupala, 2002)*

A substantial increase in population density was noted in the years 1967 and 1978, with 66 and 74 persons per hectare respectively. The city had a population of 769,445 by 1978 (Brennan et al., 2007). The city continued to grow rapidly and, by 2001, the city of Dar es Salaam had a population of about 3,000,000 people living on 57,211 hectares of built-up area, resulting in a gross density of 52 people per hectare (Lupala, 2002).

3.3 Growth of the informal settlements

Lupala (2002) noted that, up to 1940, there were only a few informal settlements. However, since 1960, the number of informal housing units has grown exponentially and now constitutes much of the informal urban fabric in Dar es Salaam (Bhanjee and Zhang, 2018). According to Kombe and Kreibich (2000), the number of squatter households in Dar es Salaam was 5,000 in 1960, but climbed to 7,000 in 1963, and then quadrupled by 1972, by when it had reached 28,000 households. Three decades later, in 2002, 1,696,500 persons (68 percent of the total population) lived in informal settlements in the city (UN-Habitat, 2010). Figure 3.2 shows the growth trend of informal settlement units between 1960 and 1979 (Kironde, 1994; Kombe and Kreibich, 2000). The growth of informal settlements takes three distinct but overlapping forms: expansion; densification, and intensification (Abebe, 2011). According to Abebe (2011), expansion can be inward, outward or independent of an existing settlement, densification refers to the infilling of the empty spaces by building structures within the existing settlements, and intensification refers to vertical increment of the built-up structures (Timoth, 1995).

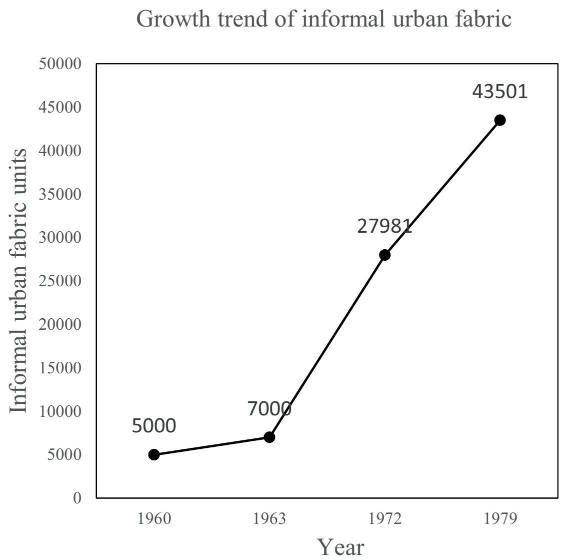


Figure 3.2 *Growth trend of informal settlements units in Dar es Salaam from 1960 to 1979. Based on data from Kombe and Kreibich, 2000.*

Dar es Salaam has expanded, and is still expanding, with most of the development informal due to the high demand for settlements caused by the population growth, including migration from other regions/cities (Peter and Yang, 2019). From 1982 to 2002, the amount of planned residential land use increased from 43 to 67 square kilometres, but the area of informal residential settlement grew from 52 to 172 square kilometres (Bhanjee and Zhang, 2018). Figure 3.3 shows the formal and informal residential development in 1982 and 2002.

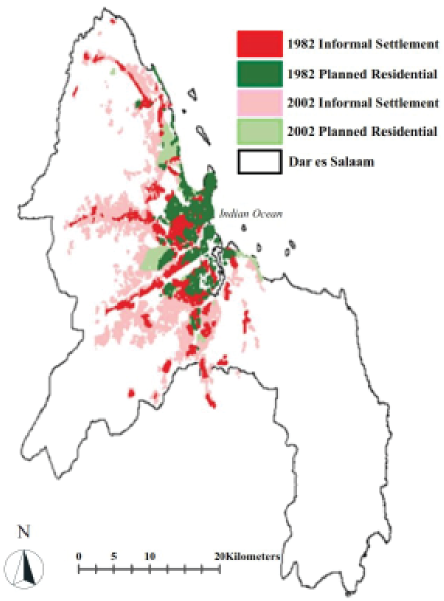
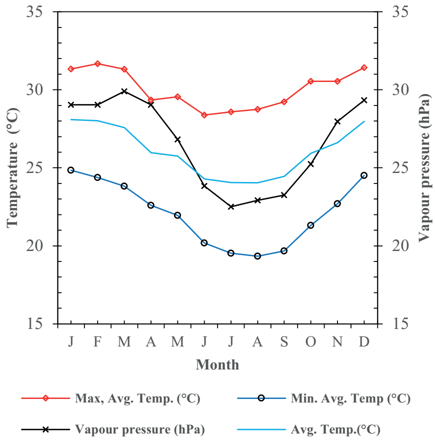


Figure 3.3 *Map of Dar es Salaam's formal and informal residential developments in 1982 and 2002. Source: Bhanjee and Zhang, 2018.*

3.4 Climate of Dar es Salaam

According to Fosberg et al. (1961) and Roth (2007), Dar es Salaam experiences a warm humid climate, referred to as *tropical wet/dry climate* (Aw) in the Köppen classification. There are two distinct seasons: wet (rainy) and dry. The climate is influenced by the monsoon winds: the northeast monsoon (NE) from March to October and the southeast monsoon (SE) from October to March (Jonsson et al., 2004), according to the passage of the inter-tropical convergence zone (ITCZ) (Iversen et al., 1984). Figure 3.4 presents climate information for the city of Dar es Salaam for the periods 2000-2009 (temperature) and 1981-2010 (radiation) as extracted from Meteotest (2014). The highest T_a are experienced in the wet season from December to April, while the dry season, with relief in thermal comfort, is between June and September. In the wet season, the monthly mean maximum T_a is 32°C (February) and the monthly mean minimum T_a is 23°C (April), while in the dry season, the monthly mean maximum T_a is 28°C (June) and monthly mean minimum is 19°C (August), see Figure 3.4 top.



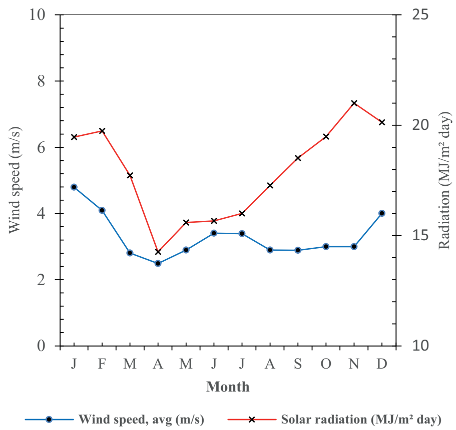


Figure 3.4 *The climate of Dar es Salaam, Tanzania. (top) Average maximum and minimum temperature and vapour pressure for 2000-2009, (bottom) mean daily wind speed for the period of 2000-2009 and global solar radiation for 1981-2010 (Source: Meteonorm v.7 (Meteotest, 2014)).*

Over the year, the mean monthly wind speed varies from 2.5 to 4.8 m/s, with the highest average wind speed typically occurring in January and the lowest average wind speed typically in April, see Figure 3.4 bottom. According to Iversen et al. (1984), the NE winds are lighter, while the SE winds are stronger. The light winds in April are primarily because this is when most of the rain falls, and there is likely no high differential surface heating between the land and the sea for the effective local sea–land breeze system to operate during this time (Nieuwolt, 1973). Occasionally local winds may be as high as 13 m/s during the afternoons, particularly from August to November (Ndetto and Matzarakis, 2014).

Relative humidity remains high throughout the year; on average it is about 75%, but it may vary from 67% in the afternoon to almost 96% at night, with April being the most humid month (Ndetto and Matzarakis, 2014). Vapour pressure is high and stable from November to April, but there is considerable drop from June to September, see Figure 3.4 top. The differences in vapour pressure mark a clear distinction between the wet and dry seasons in the city. Figure 3.5 shows mean monthly rainfall in Dar es Salaam. The annual rainfall is about 1,050 mm, with April and December being the wettest months (Ndetto and Matzarakis, 2013a). There are two distinct rainy seasons: short rains (October–December season) with a monthly average of 75-100 mm and long rains (March–May season) with a monthly average of 150-300 mm (Howorth et al., 2001).

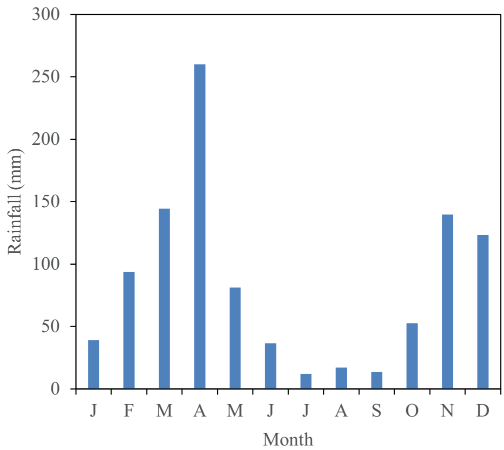


Figure 3.5 *Monthly average rainfall for 2000-2009 (Meteotest, 2014).*

The yearly maximum average values of global solar radiation occur in the period October to February, with an average of 20 MJ/(m^2 day), whereas the yearly minimum average values occur in April, 14.3 MJ/(m^2 day) (Figure 3.4 bottom).

In this thesis, the months of March and July were selected to represent the wet (warm) and dry (cool) seasons respectively. March is one of the months with highest average T_a, while July is one of the months with lowest average T_a. For March, the mean monthly maximum and minimum T_a are 31.3°C and 23.8°C respectively, while mean monthly vapour pressure is 29.9 hPa. For July, the mean monthly maximum and minimum T_a are 28.6°C and 19.5°C respectively, while the mean monthly vapour pressure stands at 22.5 hPa.

4 Methodology

In this chapter the research methods used in the thesis are presented. The thesis is inter-disciplinary in nature, drawing on different fields of study such as urban climatology, urban design and planning, and thermal comfort. The thesis therefore calls for a research design with a combination of methods to answer the identified research questions.

4.1 Research design

Harwell points out the following regarding the meaning of the term 'research design' and how it varies in different studies:

> *... in one study, research design may reflect the entire research process, from conceptualizing a problem to the literature review, research questions, methods, and conclusions, whereas in another study, research design refers only to the methodology of a study (e.g., data collection and analysis). Perhaps not surprisingly, there is variation within and between methodologies in how research design is defined (Harwell, 2011, p. 148).*

In this thesis, research design refers to the methodology of the study, including data collection and analysis. The method selected is guided by the types of research questions that the thesis seeks to address. Harwell (2011) points out how research questions are the driving force behind the choice of research design and any changes made to elements of a design as the study unfolds. Yin (2009) states that the type of research questions posed is one of the determining factors when deciding the method to use. Table 4.1 is provided to guide the research design and methodological discussions of this thesis.

Table 4.1 Research questions as a tool for research design

Research question		Aim	Approach	Methods	Research tools
		To identify and substantiate research gap	Systematic review approach	Systematic literature review	Databases: Web of Science, Engineering Village, Scopus, Lubsearch[14]
RQ1	How do urbanites in the informal settlements in the wet and dry seasons perceive the outdoor thermal environment?	Outdoor microclimate analysis	Quantitative	Micrometeoro-logical and meteorological measurements	Micrometeoro-logical and meteorological equipment measurement
		Thermal perception analysis (preference & neutrality)	Quantitative	Survey and meteorological measurements	Structured questionnaires, SPSS 20/Excel, Probit analysis & regression models
RQ2	What are the thermal comfort ranges, thermal neutrality, and thermal preference for urbanites in the informal urban fabric of Dar es Salaam for the wet and dry s easons?	To determine thermal comfort limits, neutrality, and preference	Quantitative	Survey and meteorological measurements	SPSS 20, Probit analysis & regression models
RQ3	What is the extent and variation in terms of application of different coping strategies by urbanites in the wet and dry seasons?	To identify coping strategies and the extent of their applicability	Quantitative	Survey	Structured questionnaires, SPSS/Excel
RQ4	How do urban design measures such as addition of trees with different LAI and incremental increase of building heights influence microclimate and outdoor thermal comfort?	To analyse the influence of urban design measures	Quantitative	Microclimate simulation	ENVI-met 4.4.3

14 Lund University's search engine

This thesis is based on four research questions. Table 4.1 presents a research design summary showing the aim, methodological approach and tools used in the research. Each stage represents the methodological approach for each research question.

4.2 Research approach

The general framework of this thesis uses a quantitative approach, based on the positivist research paradigm. Positivist research uses experimental designs to measure effects, and the data collection techniques focus on gathering hard data in the form of numbers to enable evidence to be presented in a quantitative form (Neuman, 2003; Sarantakos, 2005).

4.2.1 Quantitative approach

A quantitative approach can be defined as a type of empirical research into a social phenomenon or human problem, testing a theory consisting of variables that are measured with numbers and analysed with statistics in order to determine if the theory explains or predicts phenomena of interest (Creswell, 1994; Gay and Airasian, 2000). In simple terms, it can be defined as research that explains phenomena according to numerical data, which are analysed using mathematics-based methods, especially statistics (Yilmaz, 2013). The essence of a quantitative research approach in this thesis is both exploratory and explanatory. It is exploratory in the sense that the relationship between the urban fabric, outdoor microclimate, and outdoor thermal comfort in informal settlements is the phenomenon to be investigated. It is explanatory in the sense that the influence of urban fabric on the outdoor microclimate and its consequences for outdoor thermal comfort in the context of a warm humid climate must be analysed through micrometeorological measurements, questionnaire surveys, and simulations. Harwell states that:

> *The key features of quantitative studies are the use of instruments such as tests or surveys to collect data, and reliance on probability theory to test statistical hypothesis that corresponds to research questions of interest (Harwell, 2011,p.149).*

It is worth noting that the positivist research paradigm underpins the quantitative approach as the key research method: micrometeorological measurements, structured questionnaires, and microclimate simulation are thought to be objective/detached. In that respect, all methods attempt to quantify a social phenomenon, collect, and analyse numerical data, and focus on the links between a smaller number of variables. The nature of social reality for positivists is that empirical facts exist apart from personal ideas or thoughts, they are governed by laws of cause and effect, and patterns of social reality are stable and knowledge of them is additive (Marczyk et al., 2005; Neuman, 2003). In terms of its epistemology (positivist epistemology), it tries to understand a social setting by identifying individual components of a phenomenon and then explain the phenomena in terms of constructs and relationship between constructs (Cavaye, 1996). The positivists' paradigm has guided research work in the field of thermal comfort from early works, e.g. (Fanger, 1970, 1972). It is argued that no one research methodology is better or worse than any other, as all are proven to be useful in most research endeavours (Cohen et al., 2000; Silverman, 1997). What is critical is the selection of the appropriate research methodology for an inquiry at hand (Tuli, 2010).

4.3 Research methods

Research methods employed in this thesis fall into four types: systematic literature review, field survey, micrometeorological measurements, and simulation. The following is a detailed description of each of the research methods and their applications.

4.3.1 Systematic literature review

A systematic review attempts to collate all empirical evidence that fits pre-specified eligibility criteria to answer a specific research question (Liberati et al., 2009). The review uses explicit, systematic methods that are selected to minimise bias, thereby providing reliable findings from which conclusions can be drawn and decisions made (Liberati et al., 2009). This thesis uses the systematic review method to substantiate the research gap. The comprehensive review was based on a protocol; a systematic search for peer-reviewed papers in English published since 2000.

The defined criteria for identifying the relevant studies were: (1) papers that examined outdoor thermal comfort in warm/hot humid climates, (2) studies that conducted micrometeorological measurements with subjective thermal perception (questionnaire surveys), and (3) studies that link outdoor thermal comfort and the urban fabric, based on measurements and simulation. The following keywords were used: outdoor thermal comfort, thermal perception, warm/hot humid climates, and urban design/fabric. The databases were limited to Web of Science, Scopus, Lubsearch, and Google Scholar.

The selected studies were categorised according to source, year of publication, geographical location, climatic zone based on categories of warm humid climates (Kottek et al., 2006), and thermal index used. Studies on the category of the influence of urban fabric on outdoor thermal comfort were further characterised based on the method used, simulation or measurements, and whether results were quantitative or qualitative. Categorisation of the studies based on the climatic zone from 2000-2018 shows a high concentration of studies on outdoor thermal comfort in humid subtropical regions (Cfa and Cwa), compared with tropical savanna (Aw) and tropical rainforest (Af), as indicated in Table 1 of Paper I.

4.3.2 Selection of study areas

Study areas were selected by screening several informal settlements to identify those that fall into the category consolidated high-density, low-rise buildings, as identified in Lupala (2002). The typical character of these neighbourhoods is narrow and winding streets due to the compact building structures. In addition, this category of informal settlements represents most of the residential settlements where urbanites reside in Dar es Salaam (Lupala, 2002). Many of the housing areas within these settlements are only accessible by footpaths.

A pilot study was carried out in August 2016 in five informal settlements – Manzese, Tandale, Kawe, Kigogo, and Buguruni wards. Kawe and Tandale were selected as study areas for two main reasons. First, differences in distance from the sea, as one is located inland (Tandale), and the other is on the coast (Kawe). Secondly, they are representative of the majority of the informal settlements with large populations. The survey locations, Kawe and Tandale, are 1.5 and 7.2 km respectively from the Indian Ocean. Figure 4.1 shows the geographical location of the study areas within Dar es Salaam.

Figure 4.1 *Study areas Kawe and Tandale in the city of Dar es Salaam. Picture modified from (Mboera et al., 2016)*

Figure 4.2 *Location where micrometeorological measurements were taken and questionnaire surveys conducted in the Tandale area in March and July.*

Figure 4.3 *Location where micrometeorological measurements were taken and questionnaire surveys conducted in the Kawe area in March and July*

A data logger (Campbell CR800) was used to connect the sensors and 1-minute averages were sampled. Measurements were taken at a height of 1.1 m above ground level, corresponding to the average height of the centre of gravity for an adult (Mayer and Höppe, 1987). Wind speed was measured at a height of 1.5 m using a two-dimensional ultrasonic sensor (Gill Windsonic), which detects speed down to 0.02 m/s. Details on wind speed measurements are given in Papers II and III. Figure 4.2 and 4.3 shows the studied locations (Tandale and Kawe) and the position of the micrometeorological measurements. Equipment details and precision are presented in Papers II and III. The instruments used were fully exposed to solar radiation.

4.3.4 Field surveys

The pilot study had two main purposes: to test the 9-point scale (-4, very cold, -3, cold, -1, slightly cool, 0, neutral, 1, slightly warm, 2, warm, 3, hot, 4, very hot) for structured questionnaires (ISO-10551, 1995) and to choose the areas for the study. The results of the pilot study revealed that over 95% of the 200 respondents fell within the 7-point scale (ASHRAE, 2004), so the 7-point scale (-3, cold, -2, cool, -1, slightly cool, 0, neutral, 1, slightly warm, 2, warm, 3, hot) was adopted for this study. A 7-point scale has also been used in many other studies (Hwang and Lin, 2007; Ndetto and Matzarakis, 2016; Spagnolo and de Dear, 2003).

The questionnaire comprised basic personal information: gender, age, reason for and frequency of being in a particular place, time spent outdoors, and how respondents had spent the previous half hour. Respondents' thermal perception was reported on an ASHRAE 7-point scale of thermal sensation votes for outdoor conditions (Hwang and Lin, 2007; Ndetto and Matzarakis, 2016). The scale is −3, cold; −2, cool; −1, slightly cool; 0, neutral; 1, slightly warm; 2, warm; and 3, hot. Respondents' preference for different weather variables was reported on a 3-point scale according to McIntyre (1980). The type of clothing and activity were observed by the interviewer and chosen from a predefined list. The questionnaire is shown in Appendix 1.

The actual fieldwork was conducted on 16-20 March and 25-28 July 2017, during the warmest hours of the day (11:00-16:00). A total of 1541 random respondents were interviewed, 746 during the wet season and 795 during the dry season. The details and characteristics of respondents, along with the protocol of the survey exercise, are presented in Papers II and III.

4.3.5 Microclimate simulation

This thesis adopts simulation as one of the methods to investigate the influence of the urban fabric on both outdoor microclimate and thermal comfort through selected measures. The nature of the microclimate can be depicted by measurements of temperature, humidity, and wind speed, but the complex link between microclimate and urban fabric can be more efficiently depicted by the simulation method. As Grout and Wang describe:

> *Simulation is a remarkably ubiquitous research design, which can be deployed across a broad range of topics, for purposes that span from highly targeted applications in design projects to theory building. Just as significantly, simulation frequently lends itself to many uses as a tactic within other research strategies, or as a full partner in combined strategies (Grout and Wang, 2013, p. 349).*

This thesis makes use of modelling. Since the study considers the informal urban fabric, various conditions and challenges have to be taken into account. The chosen simulation model (ENVI-met 4) has the capability to simulate the state of the atmosphere by combining the influence of buildings, vegetation, surface characteristics, soils, and climatic contour conditions (Bruse and Fleer, 1998), see Section 4.4.3. Measures such as use of trees with different LAI and different building heights are applied and their influence analysed. Despite having three categories of LAI for analysis, it is worth noting that ENVI-met simulation of vegetation was based on leaf area density (LAD[15]). Equation 4.1 (Bruse and Fleer, 1998; Morakinyo et al., 2017), which shows the relationship between the two, was used to estimate the respective LAD for each tree height:

$$LAI = \int_{0}^{h} LAD(z)dz \tag{4.1}$$

where:

h is the height of the tree (m), dz is the vertical grid size (m), LAI is the leaf area index (m^2/m^2), and LAD is the leaf area density (m^2/m^3). The scenarios used for the analysis are presented in Table 4.2. In this study, the tree used had a height of 10 m.

Simulation scenarios

The informal settlement of Tandale was chosen for the simulation study. Simulation was based on three scenarios: incremental increase in height of buildings, addition of trees with different LAI and combination of trees with different LAI, and incremental increase in building height in the street canyon. As noted by Šliužas (2004) and Abebe (2011), densification of informal settlements via incremental housing construction is the major aspect of informal settlement development process apart from expansion. Receptors[16] were used to analyse both the existing condition and the influence of various design parameters on microclimate and outdoor thermal comfort. The six receptors were located in similar positions for different simulation scenarios as indicated in Figure. 4.4 and 4.5. Figure 4.4 shows that the receptors were located in the widest part of the street canyon, next to an open space used for car parking. Figure 4.4 was generated from ENVI-met Monde, see Section 4.4.3. Figure 4.5 shows the scenarios for incremental increase of building heights in a street canyon to heights of 12 m, 18 m, and 24 m. Average values of data for the six receptors for both microclimate and thermal comfort

[15] LAD is a parameter defined as the total one-sided leaf area (m^2) per unit layer volume (m^3) in each horizontal layer of the tree crown (Lalic and Mihailovic, 2004).

[16] Receptors are virtual 'climate stations' that enable the state of the model to be followed in greater detail at specified points.

were analysed. Cross-sectional representation of Figure 4.5 is shown in Figure 4.6. Table 4.2 presents the simulation scenarios.

The base case comprises the existing model of Tandale in which no measures were employed (Figure 4.4). The existing situation was analysed to gain an insight into the nature of the informal urban fabric in terms of microclimate and thermal comfort. The microclimate variables analysed were T_a and T_{mrt}.

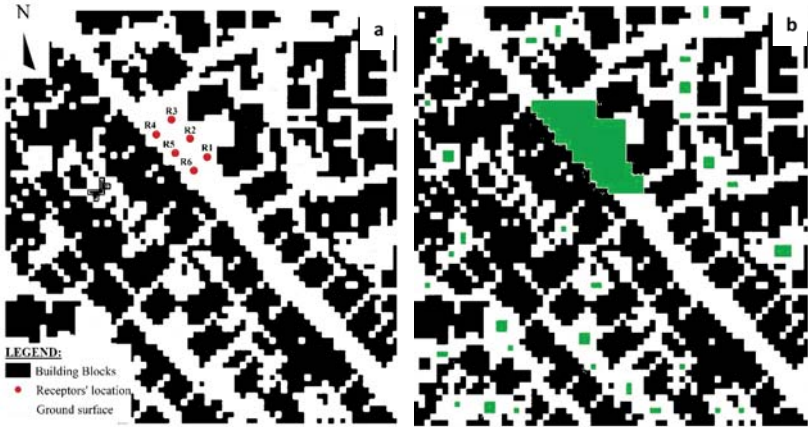


Figure 4.4 *Location of (a) receptors and (b) trees added in the informal urban fabric of Tandale. The location marks the area where micro-meteorological measurements were taken.*

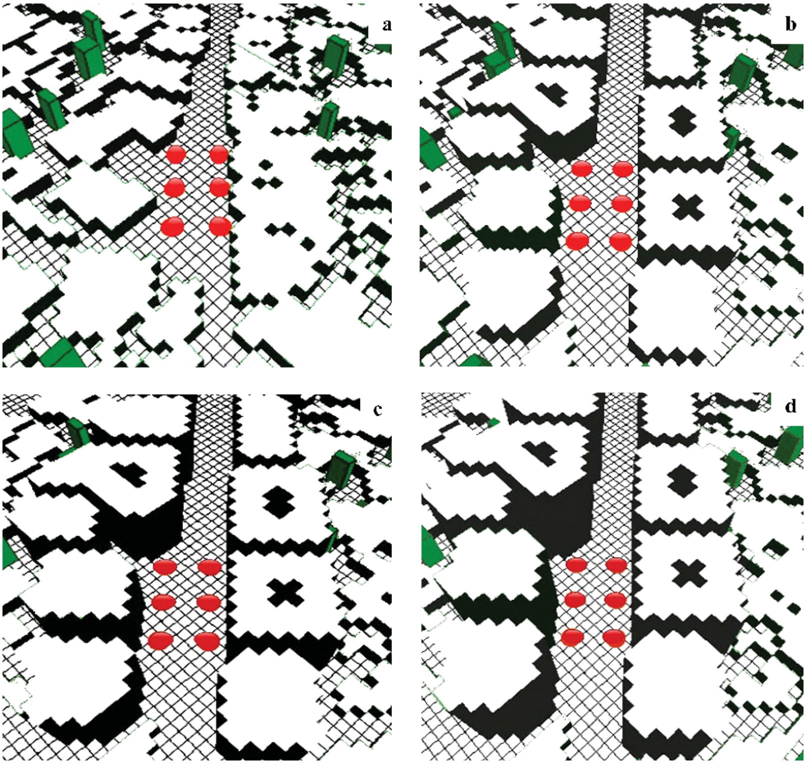


Figure 4.5 *A 3-D representation of (a) existing 4-m height model (b) 12-m height model (c) 18-m height model, and (d) 24-m height model for the Tandale informal urban fabric area.*

Table 4.2 Simulation scenarios, scenario code, urban design measure and their objectives.

Simulation scenarios	Scenario code	Measures employed within the informal urban fabric	Simulation objective for analysis
	Base case	None (4m heigh buildings)	Analyse existing condition
1	LAI 2	Addition of trees (LAI 2) to the existing model	Analyse the influence of use of trees in the existing situation
	LAI 4	Addition of trees (LAI 4) to the existing model	
	LAI 6	Addition of trees (LAI 6) to the existing model	
2	H12M	Increase of height to 12 m (4 storeys)	Analyse the influence of changing building heights
	H18M	Increase of height to 18 m (6 storeys)	
	H24M	Increase of height to 24 m (8 storeys)	
3	H12M-LAI 6	Increase of height to 12 m and trees of LAI 6	Analyse the influence of combining changes in building heights and LAI 6
	H18M-LAI 6	Increase of height to 18 m and trees of LAI 6	
	H24M-LAI 6	Increase of height to 24 m and trees of LAI 6	

A detailed explanation of calibration, parameters of simulation, input data, and other parts of the simulation procedure can be found in Paper IV.

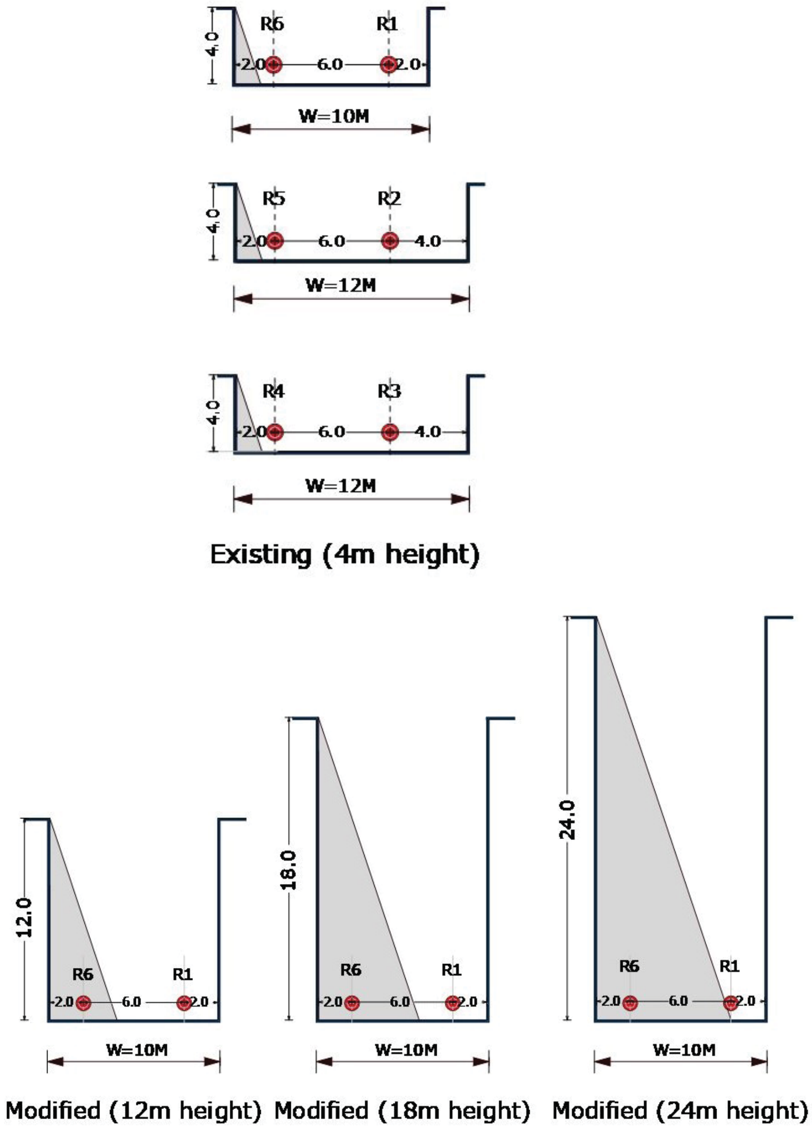


Figure 4.6 *A schematic illustration of urban canyons for the scenarios that involve changes of height from existing low-rise (4m) to 12 m, 18 m, and 24 m. Red dots indicate position of receptors.*

4.4 Analysis tools

4.4.1 Thermal indices

In this thesis three thermal indices, PET, SET*, and UTCI, were used. PET and SET* were used to enable comparison with previous studies conducted in warm humid climate regions, whereas UTCI was used to test its applicability in a warm humid climate, as it was developed to represent all types of climates (Blazejczyk et al., 2012). The indices are described in Section 2.1.7.

4.4.2 Probit analysis

Probit analysis[17] is a type of regression used to analyse binomial response variables. Probit is essentially a mathematical transformation to linearise a set of data forming a sigmoid response curve that enables the parameters of the curve to be determined along with their statistical significance. The Probit analysis deals with two levels of response to a variable (Ballantyne et al., 1977). For thermal perception votes on a 7-point scale, the two responses could be arranged in several ways but preferably by splitting the neutral perception votes into two groups: warmer than neutral (½ (0), +1, +2, +3) and cooler than neutral (½ (0), -1, -2, -3).

Probit analysis is applied to these data to produce the smoothed curve, which is a typical cumulated normal frequency distribution curve. The curve shows the total percentage of people who would change their assessment from 'cooler than neutral' to 'warmer than neutral' at that temperature. This is the same percentage as will be obtained by exposing a random sample of the population to a given temperature and measuring the percentage of those who will assess their thermal perception as 'cooler, neutral or warmer' (Ballantyne et al., 1977).

A neutral temperature may be defined as the temperature at which there are equal probabilities of a particular vote being cast for the lower or higher of the two categories of thermal perception under consideration. This is also the temperature at which ½(0)+(1)+(2)+(3) = 50%, a fact which follows from the relationship of the normal distribution curve to its cumulative curve (Ballantyne et al., 1977).

[17] Probit analysis is a method of analysing the relationship between a stimulus (dose) and the quantal (all or nothing) response.

4.4.3 ENVI-met version 4.3.3

ENVI-met is an advanced simulation software that recreates the microclimatic dynamics of the outdoor environment by enhancing the interaction between climatic variables (e.g. T_a, humidity, air movement and solar radiation), vegetation, surfaces, soil, and the built environment (Bruse and Fleer, 1998). The new features in ENVI-met 4.3.3 (Scientific Version) include the simple forcing of T_a and air humidity at 2 m height, which needs input data, such as the initial temperature of the atmosphere. Simple forcing enables the software to account for atmospheric temporal variations and thereby represents better the evolution of meteorological variables through the day (Acero and Arrizabalaga, 2016) than previous versions of ENVI-met (i.e. version 3.1). The forcing also has the option to input on an hourly basis the values that are collected either from weather stations or directly from on-site measurements. Apart from the previous 1D vegetation module (i.e. plants are modelled as vegetation columns), version 4.0 implements a new 3D vegetation module to describe varied shapes of plants and spatial distribution of the leaves. Version 4 also accounts for the thermal inertia of walls and roofs (Bruse, 2014).

In documenting the informal urban fabric in different areas, the study used ENVI-met Monde, which is a vector-based editing system designed to bridge the gap between the vector-based tools such as GIS and Open Street Maps and the raster-based ENVI-met (Bruse, 2015). It has the advanced option of importing Open Street Maps Geo-data and opportunity to edit building geometry using an integrated editor, making it possible to create the ENVI-met model by transforming the complex geometry of informal urban fabric areas. ENVI-met Biomet 1.5 (Bruse, 2015) was used to calculate the thermal comfort indices.

5 Results

In this chapter the most important findings of the study are presented. The chapter is divided into two parts. The first section discusses results from the analysis of micrometeorological measurements and structured questionnaires conducted in the informal settlements of Kawe and Tandale for both wet and dry seasons. The second part presents results from simulations that focus on the informal settlement of Tandale in the wet season.

5.1 Urbanites' thermal perception

5.1.1 Influence of micrometeorological variables

Results show that T_a strongly influences mean thermal perception votes (MTPV) of the respondents in both the wet (warm) season (R^2 = 0.93) and the dry (cool) season (R^2 = 0.73) for both settlements, see Figure 5.1a. The T_{mrt} also shows a strong relationship with the respondents' mean thermal perception votes (MTPV) in both informal settlements. The relationship is more pronounced in the wet season (R^2 = 0.81) than in the dry season (R^2 = 0.67) Figure 5.1b. It was revealed that respondents experience the same magnitude of T_{mrt} differently depending on the season – the neutral T_{mrt} = 47.3°C in the dry season and the neutral T_{mrt} =32°C in the wet season (Figure 5.1b). Consequently, in the dry season when the air humidly is low and the nights are cooler, people tend to tolerate higher T_{mrt} during the day. It should be noted that no relationship was found between thermal perception and vapour pressure within each season. However, similar to T_a and T_{mrt}, the mean thermal perception votes were much higher in the wet season.

It was observed that a combination of low vapour pressure and slightly lower T_a defines the dry season. In the analysis, it was found that what respondents are referring to as a dry season is more characterised by a considerable drop of vapour pressure and a slight drop in T_a, as indicated in Figure 5.2.

Considerable seasonal differences in MTPV and micrometeorological variables were observed. Unlike the wet season, which presents strong heat stress, the dry season presents comfortable conditions for most urbanites as they were within acceptable ranges (-1,0,+1) as shown in Figure 5.1a & b. There was no significant relationship between vapour and MTPV (Figure 5.1c).

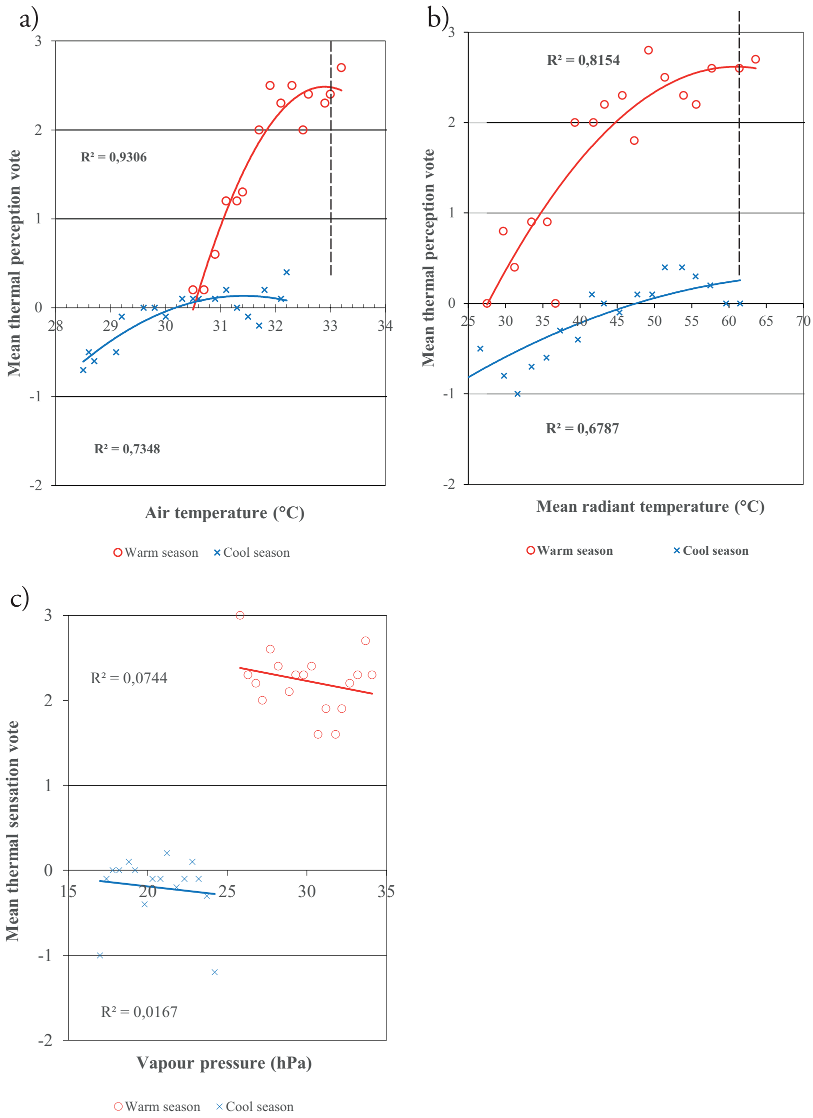


Figure 5.1 *The relationship between MTPV and meteorological variables for the wet and dry seasons.*

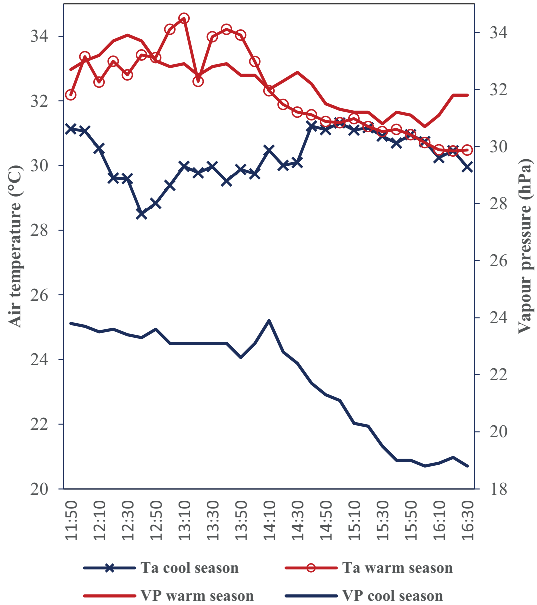


Figure 5.2 *Comparison of micrometeorological measurements (T_a and vapour pressure) in the wet and dry season at the site (Tandale).*

5.1.2 Thermal comfort ranges

In the wet season, a narrower interval of comfort (2.3-4°C) was found for the three indices than in the dry season (9-17°C). It is evident that the biggest challenge in the dominant wet season is linked to the high and narrow comfort range experienced by urbanites in the informal settlements. Table 5.1 shows acceptable ranges in which for the wet season, PET, SET* and UTCI had a range of 4.0°C, 4.0°C , and 2.3°C respectively. In the wet season, both UTCI and PET were found to have a significant relationship with X^2 (15) = 28.0; p = 0.022 and X^2 (27) = 74.3; p < 0.001 respectively.

Table 5.1 Neutral and preferred index values, thermal acceptable ranges, and upper thermal comfort limits (80% thermal acceptability) for the wet, dry, and combined seasons (Chi-square test performed at 95% confidence level, 0.05 significance level).

		Neutral index temperature value by Probit technique		Neutral index temperature value by regression	Preferred index temperature value by Probit technique		Thermally acceptable ranges by regression lines	Upper comfort limit (80% acceptability*)
Index	Season	$T_{neut.}$ (°C)	Chi-square test of independence	$T_{neut.}$ (°C)	$T_{pref.}$ (°C)	Chi-square test of independence	(°C)	(°C)
UTCI	Wet	29.5	X^2 (15)=28.0; p=0.022	31.3			30.2-32.5	32.5
	Dry	36.0	X^2 (13)=8.85; p=0.784	35.1	26.5	X^2 (13)=13.63; p=0.400	30.6-39.5	40.5
	Combined	33.8	X^2 (19)=48.7; p=0.000	32.1	25.0	X^2 (9)=21.9; p=0.090	29.7-34.6	33.5
SET*	Wet	26.7	X^2 (20)=17.5; p=0.618	25.3			23.4-27.4	27.7
	Dry	33.5	X^2 (17)=9.05; p=0.939	31.3	22.0	X^2 (17)=6.96; p=0.984	27.5-36.5	39.4
	Combined	30.9	X^2 (22)=45.2; p=0.002	27.6	21.6	X^2 (15)=11.8; p=0.697	23.9-31.4	30.3
PET	Wet	27.5	X^2 (27)=74.3; p<0.001	27.7			25.8-29.8	30.2
	Dry	39.5	X^2 (23)=14.5; p=0.912	39.1	25.5	X^2 (23)=18.7; p=0.718	30.6-47.6	48.2
	Combined	33.5	X^2 (19)=22.3; p=0.270	30.2	21.5	X^2 (19)=20.7; p=0.353	27.4-33.6	31.8

* 80% acceptability refers to the thermal conditions found to be acceptable by 80% of respondents.

5.1.3 Thermal neutrality

In this study, the neutral temperatures in the wet and dry seasons were determined through both regression and Probit techniques (Ballantyne et al., 1977). A summary of the results with their statistical significance is presented in Table 5.1. The neutral temperature in the wet season for UTCI and PET shows marginal differences between regression and the Probit technique. For the wet season, the neutral temperature determined by Probit analysis for both UTCI and PET show statistical significance, with p = 0.022 and p = 0.001 respectively. Nonetheless, for the wet and dry seasons, results show neutral index temperature differences ranging from 4 to 11°C, with neutral temperatures higher in the dry season than the wet season.

5.1.4 Thermal preference

A large difference was observed between the index temperatures that respondents prefer and the neutral index temperature, as indicated in both Papers II and III for PET, SET* and UTCI. The preferred temperatures are lower by 9-12°C than the neutral temperatures (Table 5.1). This shows that urbanites felt comfortable at higher index temperatures than they usually prefer. This finding concurs with the findings of previous studies (Johansson et al., 2018; Lin, 2009; Yang et al., 2013). Studies such as Spagnolo and de Dear (2003), Hwang and Lin (2007) and Johansson et al. (2018) noted that it is normal for people in warm climates to prefer lower temperatures, and the urgency of expectation regarding comfortable thermal conditions increases with the difference between the neutral and preferred temperature. The large difference found in the informal urban fabric areas indicates a lack of adaptive options in the respondents' outdoor environment.

5.1.5 Urbanites' coping strategies

Most urbanites tend to seek shade during a walk as well as use hand fanning with, e.g., a newspaper; both strategies were used by over 95% of respondents during high thermal stress conditions in both seasons. Seasonal differences were observed, as cold drinks are more widely used in the wet season (75%) than in dry season (51%). In informal settlements, urbanites seek shade under the limited number of available trees or man-made shading devices, and often the house veranda, since there is no overhead shading in the street. It was found that both front and rear verandas were used, depending on the position of the sun. No differences were found in clothing values between seasons; it was 0.52 clo on average. However, there was a slight tendency to change clothing more often in the dry season (61%) than in the wet season (47%). Only 2% of the urbanites used parasols for shading.

5.1.6 Performance of thermal indices used

In the wet season, a strong relationship was found between the thermal indices used with respondents' MTPV. All three indices, SET*, UTCI, and PET, showed good correlation with MTPV, as described by a polynomial function curve (Figure 5.3). The horizontal dashed line shows the acceptable comfort limits. Statistically, UTCI performs better than SET* and PET in the wet season, as shown in Table 5.1. A chi-square test for the neutral temperature in the wet season shows a statistically significant relationship between respondents' TPV and UTCI, X^2 (15) = 28.0; p = 0.022. It is worth noting that while SET* incorporates actual observed values of clothing insulation and metabolic rate, UTCI incorporates clothing as a function of T_a and metabolic rate as a function of walking speed, while PET has a fixed clothing and activity level. At higher index temperatures, respondents' MTPV decreases as index temperature increases (Figure 5.3). For PET and UTCI, the polynomial function shows lower MTPV of respondents as index temperature increases from 42°C and 44°C respectively.

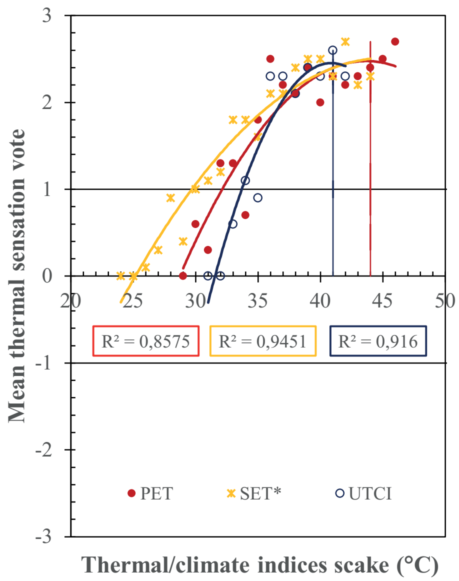


Figure 5.3 *The relationship between mean thermal perception vote and thermal indices for the wet season.*

5.2 Urban design measures to improve the thermal comfort conditions

The findings presented in this section are divided into three parts, based on the simulated measures employed in the informal urban fabric: application of trees with different LAI, incremental increase of building heights on both sides of the street canyon, and combined increase of building height and trees with different LAI.

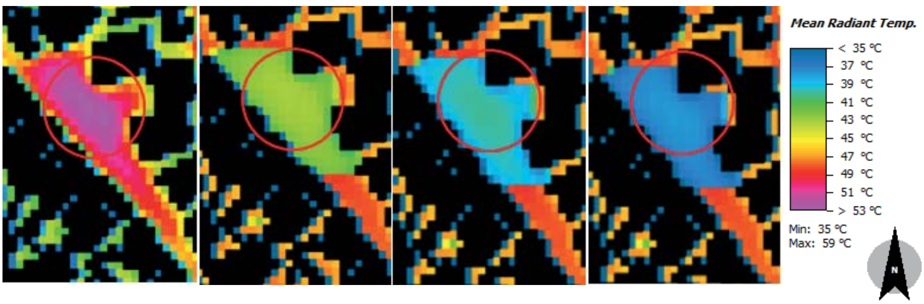
5.2.1 Influence of trees with different LAI

Adding trees with LAI of 2, 4, and 6 to the base case (existing condition) results in a marginal reduction of T_a but a noticeable reduction of T_{mrt}. Application of trees with LAI of 2, 4, and 6 leads to a decrease of T_{mrt} of 7.9, 10.1, and 12.2°C respectively (Figure 5.4). In Figure 5.4, the circles show the areas where measures were applied. Application of trees with LAI of 6 has a potential to reduce T_{mrt} to the neutral T_{mrt} of 32°C in the wet season (see Paper IV).

With regard to outdoor thermal comfort, it was found that addition of trees leads to a considerable reduction of PET in the warmest part of the day (11:00-16:00) in the wet season. It was noted that LAI of 2, 4, and 6 reduces PET by 3.7, 4.7, and 5.6°C PET respectively at 14:00 (Figure 5.6).

(a) Influence of trees on T_{mrt}

Base case LAI 2 LAI 4 LAI 6



(b) Influence of trees on PET

Base case LAI 2 LAI 4 LAI 6

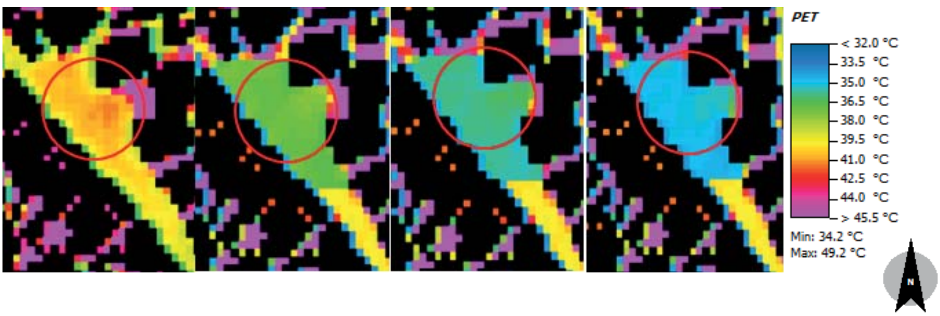


Figure 5.4 *The influence of trees on (a) T_{mrt} and (b) outdoor thermal comfort (PET) at 14:00 (20 March 2017) in the Tandale area. The red circle is the location of receptors and where trees were employed.*

5.2.2 Influence of different building heights

It was found that incremental increase of the building height from the base case (4 m, existing condition) to the maximum height of 24 m influences both microclimate and outdoor thermal comfort. The influence of the increase in building height is noticeable from 11:00 to 17:00, but it does not considerably reduce T_a (as shown in Paper IV), which indicates weak relationship between urban geometry and T_a. Conversely, an increase of building height was found to considerably reduce T_{mrt} and improve outdoor microclimate. Incremental increase in building height to 12, 18, and 24 m was found to reduce T_{mrt} by 7.2, 9.4, and 11.2°C respectively at 14:00 (Figure 5.5a).

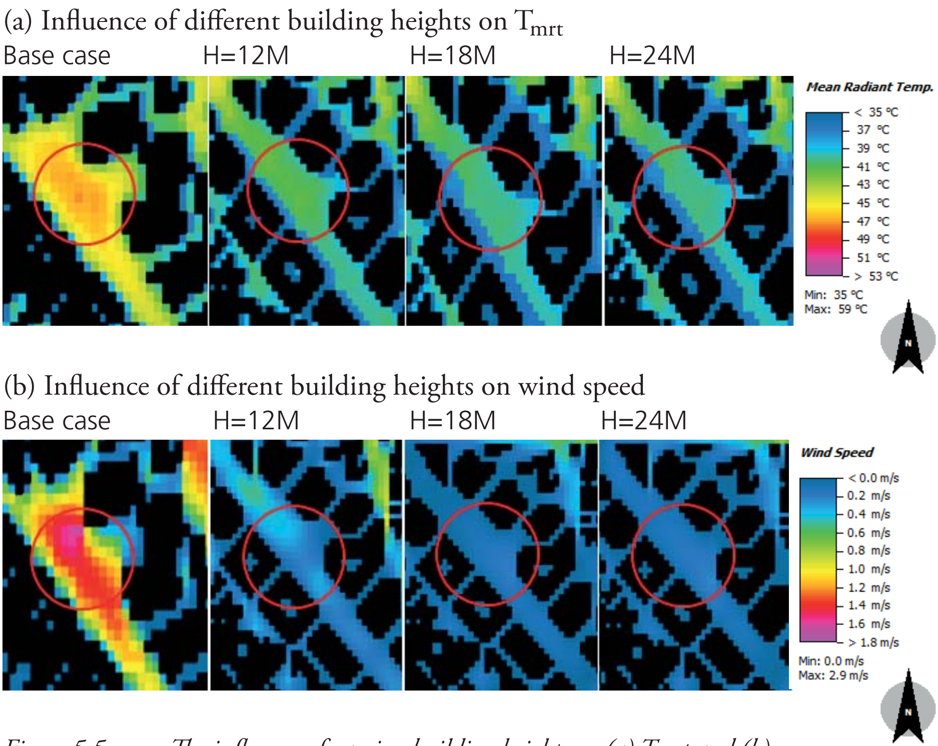


Figure 5.5 The influence of varying building heights on (a) Tmrt and (b) wind speeds in Tandale at 14:00 (20 March 2017). The red circle is the location of receptors.

The incremental increase of building height was found to decrease the wind speed from an average of 1.4 to below 0.5 m/s (Figure 5.5b). Moreover, considerable improvement of the outdoor thermal comfort through reduction of PET was found. An incremental increase in building height from a single storey (4m) to 12, 18, and 24 m height reduces maximum PET at 14:00 by 2.5, 2.8, and 3.8°C respectively (Figure 5.6a).

5.2.3 Influence of combining increased building height and trees

The combined influence of an incremental increase in building height to 12, 18, and 24 m and adding trees with LAI of 6 improves both microclimate and outdoor thermal comfort. The maximum reduction of T_a (0.25°C) was found at the building height of 24 m and a LAI of 6 at 14:00 (Paper IV, Fig. 12). A substantial decrease in T_{mrt} was noted for combinations of heights of 12 m, 18 m, and 24 m with LAI of 6, resulting in a decrease of T_{mrt} by 12.3, 14.4, and 15.1°C respectively (Fig. 8b, Paper IV). The combination of incremental increase in building height and trees provides the maximum improvement of the outdoor microclimate, and neutral T_{mrt} could be attained by combining heights of 18 m and 24 m with LAI of 6.

However, there were rather small differences for different heights on the reduction of PET, as indicated in Figure 5.6c. The maximum reduction of PET, 6.4°C, was found at 16:00. Comparative analysis shows that, when combining both increased building height and trees with high LAI, it is the tree that makes the biggest contribution to the reduction of PET, as shown in Figure 5.6, at least for high values of LAI.

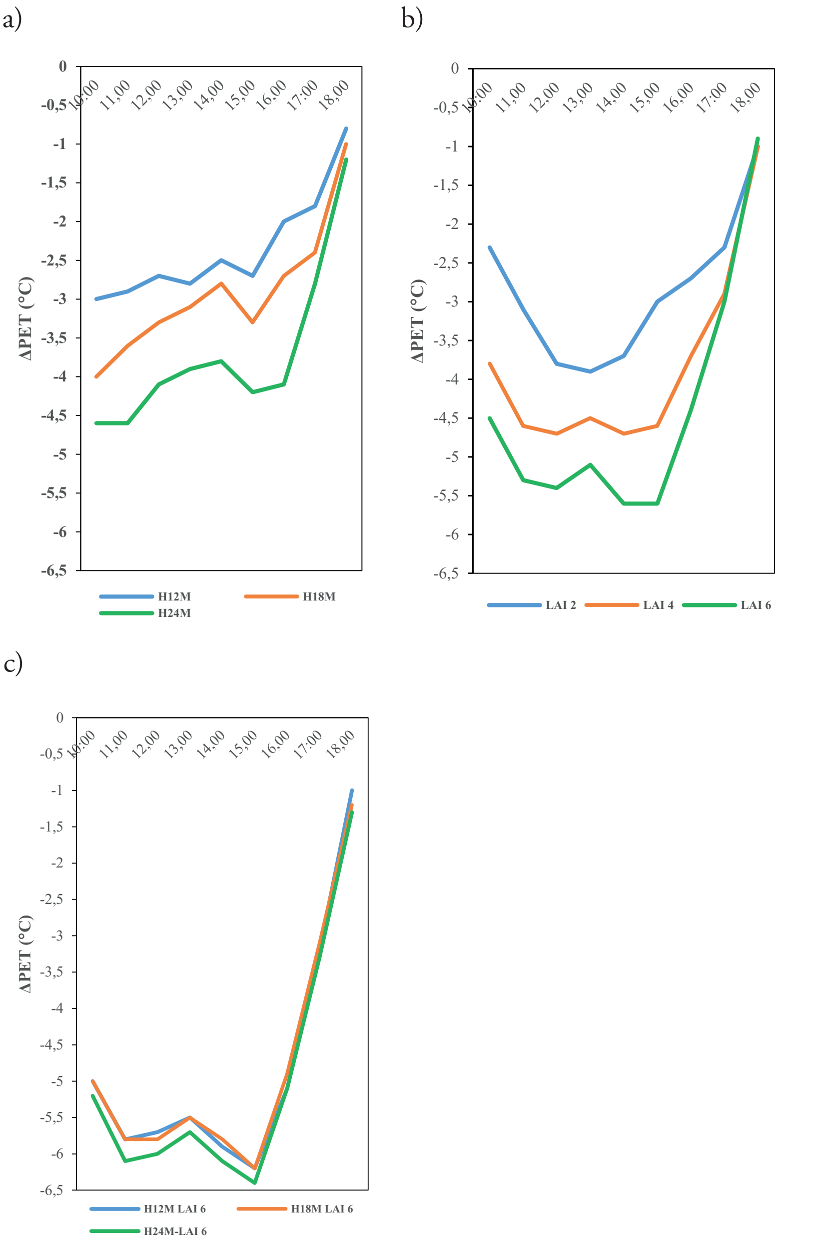


Figure 5.6 *The reduction of PET for different thermal comfort measures: (a) varying height of buildings, (b) use of trees with different LAI, and (c) combination of variation of building heights and trees with LAI of 6.*

6 Discussion

The findings presented in this thesis may contribute to the improvement of the outdoor thermal environment in informal settlements and the overall aim of Sustainable Development Goal 11 in two ways. First, knowledge on thermal comfort limits within the informal urban fabric can be used as a guiding tool in urban design. Secondly, by implementing appropriate urban design measures, the thermal environment of informal settlements will be improved. By taking into account that the majority of urbanites in developing countries live in informal settlements, the findings of this thesis can be a useful knowledge base for similar studies in informal settlements in other warm humid regions.

6.1 Urbanites' thermal perception

This study investigated urbanites' thermal perception in two informal settlements, Tandale and Kawe. Findings suggest that urbanites in these informal settlements experience extreme thermal challenges, and the results shed light on the outdoor thermal comfort challenges experienced. Sixty-four percent of respondents lived and 28% worked in the studied informal settlements (Paper II). Consequently, in the wet season that dominates the year (October-May), urbanites in these informal settlements suffer from heat stress most of the time, as their thermal perception is above the thermally acceptable ranges (Papers II & III). Urbanites in the informal urban areas were also found to have limited adaptive options (Baruti and Johansson, 2020). This is shown by the narrow thermal acceptable ranges found in the informal urban areas, unlike in the formal urban areas where there are more options to find shade under arcades, shading screens, or trees. In another study (Li et al., 2016a) conducted in a residential community (planned area), adaptive options, e.g. sunshades, were shown to improve residents' thermal acceptability.

6.1.1 Influence of micrometeorological variables

In this study it was found that T_a, T_{mrt}, and vapour pressure were major meteorological variables determining thermal perception. T_a strongly influences urbanites' thermal perception in both the wet season (R^2 = 0.88) and the dry season (R^2 = 0.73). Other studies (Villadiego and Velay-Dabat, 2014; Zeng and Dong, 2015) also found a strong connection between T_a and thermal perception votes of respondents. Villadiego and Velay-Dabat (2014) found respondents were sensitive to very small variations of T_a in the warm humid tropical savannah climate of Barranquilla, Colombia, which is dominated by small diurnal and annual variations of T_a (24-32.3°C). In this study, the respondents' sensitivity to the narrow range of T_a is also noted. However, the noticeable relief experienced by respondents in the dry season, despite the T_a being slightly lower, is believed to be associated with the large decrease in vapour pressure.

The strong heat stress caused by a combination of high T_a, T_{mrt}, and high vapour pressure experienced in the wet (warm) season shows that the urbanites are sensitive to any slight change in the outdoor thermal conditions. A slight decrease of T_a and a substantial decrease in vapour pressure brings substantial thermal relief, as shown by the number of respondents within the comfort range in the dry (cool) season. Higher vapour pressure in warm humid climates reduces evaporative cooling from the skin and increases thermal discomfort (Johansson, 2016). Similar results were found by Villadiego and Velay-Dabat (2014).

T_{mrt} shows a stronger relationship with the respondents' MTPV in the wet season (R^2 = 0.81) than in the dry season (R^2 = 0.67). Determining the neutral T_{mrt} by Probit analysis for the wet and dry seasons shows that respondents experience the same magnitude of T_{mrt} differently depending on the season. Explicitly, the influence of neutral T_{mrt} = 47.3°C in the dry season is equal to the neutral T_{mrt} = 32°C in the wet season (Fig. 10, Paper III). This is associated with the psychological influence of the long, wet season, which is accompanied by high T_a and air humidity; the lower vapour pressure in the dry season presents substantial relief, as it facilitates evaporative cooling from the skin.

6.1.2 Thermal comfort ranges

It was found that, in the wet season, there is a narrow interval of comfort ranges (2-4°C) for the three thermal indices. Apart from being narrow, they were higher (e.g. 30.2-32.5°C UTCI, 25.8-29.8°C PET, 29.7-34.6°C SET*), compared to other climates. Previous studies in warm humid climates, such as Li et al. (2016a), Johansson et al. (2018), and Ndetto and Matzarakis (2016), also found higher thermal acceptable ranges compared to those in cold and temperate climates. Two observations could explain this. First, structured questionnaires and meteorological measurements were conducted at the warmest time of day, and consequently, a large percentage of the TPV was concentrated to high index temperatures. It is evident that the biggest challenge of the dominant wet season is linked to the high and narrow comfort range. This implies that, in the wet season, urbanites in these informal settlements suffer because their thermal perception is above the thermally acceptable ranges for a longer period. Secondly, small variations of microclimatic conditions in the warm humid tropical savannah climate when compared to other climates leads to narrow thermal comfort range. On the other hand, the dry season presents large comfort ranges, 9-17°C, for the three indices. The lower T_a and vapour pressure during the dry season results in considerable relief in the thermal perception, as can be observed in Fig. 5a-Paper II, which shows that the majority voted within the comfort range during the dry season.

A comparison with other studies in warm humid climates using the same indices (Table 6.1) indicates that urbanites in the informal urban areas experience thermal comfort ranges that, in general, have a narrower range but higher index temperatures, especially in the dominant wet season, compared to formal areas. The findings show the higher level of tolerance and strength of adaptation of the urbanites in the informal urban areas. Other studies (Knez and Thorsson, 2006; Li et al., 2016a; Lucchese et al., 2016) indicated that urbanites in different regions have different thermal requirements, due to thermal adaptation. Despite the fact that thermal indices are used to compare studies in different regions, it is worth pointing out that other factors, such as differences in the type of measuring equipment and their set-up, can make comparison difficult.

Table 6.1 Comparison of thermally acceptable ranges for UTCI, SET*and PET in warm humid climates.

City, Country	Context	Thermal Indices	Acceptable index temperature ranges (°C)			Source
			Wet season	Dry season	Combined season	
Tropical savanna (Aw)						
Dar es Salaam, Tanzania	Informal	UTCI SET*	30-32 23-27	31-40 28-37	28-35 24-31	Baruti et al, 2020
Dar es Salaam, Tanzania	Formal/ planned	PET	23–31			Ndetto and Matzarakis (2016)
Dar es Salaam, Tanzania	Informal	PET	26-30	31-48	27-34	Baruti and Johansson, (2020)
Guayaquil, Ecuador	Formal/ planned	SET* PET	Upper 25 Upper 25	Upper 31 Upper 34	Upper 29 Upper 31	Johansson et al. 2018
Humid subtropical (Cfa & Cwa)						
Taichung, Taiwan	Formal/ planned	SET*			20–35	Hwang and Lin, 2007
Wuhan, China	Formal/ planned	SET*			23-29	Zhou et al., (2013)
Hong, Kong	Formal/ planned	UTCI			20-27	Huang et al. 2017
Wuhan, China	Formal/ planned	UTCI			15-23	Huang et al., (2016)
Changsha, China	Formal/ planned	PET			15–22	Liu et al. (2016)
Hong Kong	Formal/ planned	PET	27–29	14–16		Ng and Cheng (2012)
Chengdu, China	Formal/ planned	PET	20–30			Zeng and Dong (2015)
Sun Moon Lake, Taiwan	Formal/ planned	PET			26–30	Lin and Matzarakis (2008)

Unlike the study by Yahia and Johansson (2013) conducted in a hot-arid climate, which showed that people who do not have air-conditioning have a wider comfort range, it was shown that urbanites in the informal settlements, who do not have access to air-conditioning at home, have a narrow comfort range. It can be argued that small variations of microclimatic conditions in the warm humid tropical savannah climate produce a narrower thermal comfort range than in other climates. In these informal settlements, factors such as very low wind speeds may contribute to uncomfortable thermal conditions, as wind movement is crucial for reducing heat stress in a warm humid climate (Ahmed, 2003; Makaremi et al., 2012; Ng and Cheng, 2012), specifically when

T_a is lower than the skin temperature. However, the effect of wind is included in the PET.

6.1.3 Thermal neutrality

Neutral temperature, the index temperature at which people feel neither warm nor cold, was determined for three indices: PET (Paper II), SET*, and UTCI (Paper III). It was observed that the neutral temperatures were high. High neutral temperature in warm environments implies thermal adaptation among respondents (Hwang and Lin, 2007). The neutral temperature was also shown to be higher in the dry season than the wet season (see Table 5.1); this was also found in other studies (Johansson et al., 2018; Spagnolo and de Dear, 2003; Yahia and Johansson, 2013). Since the average clothing value was the same in both seasons, it can be argued that the difference in neutral index temperatures is the result of the effect of seasonal adaptation and that it is more of a psychological than behavioural adaptation.

6.1.4 Thermal preference

The index temperatures that respondents prefer were observed to be much lower than the neutral index temperatures, as indicated in both Papers II and III for PET, SET* and UTCI. This shows that urbanites felt comfortable at higher index temperatures than they usually prefer. This finding concurs with the findings of several studies (Johansson et al., 2018; Lin, 2009; Yang et al., 2013). Studies such as Spagnolo and de Dear (2003), Hwang and Lin (2007) and Johansson et al. (2018) noted that it is common for people in warm climates to prefer lower temperatures, and the expectation regarding comfortable thermal conditions increases with the difference between the neutral and preferred temperature. The large difference among the urbanites in the informal urban areas of this study indicates lack of adaptive options in the outdoor environment.

6.1.5 Urbanites' coping strategies

A number of behavioural adaptation measures, such as change of clothing, seeking shade, and changing drinking habits among the urbanites, were shown by the questionnaire survey. The greater preference to use cold drinks in the wet season than in the dry season has also been observed in other studies (Li et al., 2016a; Tung et al., 2014; Watanabe and Ishii, 2016; Yang et al., 2013). Behaviour such as seeking shade on a walk or sitting under trees or house verandas during high thermal stress conditions was reported by over 95% of respondents. Johansson et al. (2018) also observed a shade-seeking tendency. Only 2% use a parasol for shading which is considerably less than that found studies by Tung et al. (2014) and Johansson et al. (2018). No differences were found in average clothing values between seasons, and this was also noted in other studies (Johansson et al., 2018; Makaremi et al., 2012) in the tropical rainforest climate (Af). It is worth noting that the average clothing value in the informal settings was slightly higher than in the formal areas (Ndetto and Matzarakis, 2016), as clothing style in informal urban fabric areas is more conservative.

6.1.6 Performance of thermal indices used

In this study, the three rational thermal indices, PET, SET*, and UTCI, were used. In the dominant wet season, good correlations were found for all thermal indices with MTPV, with R^2 above 0.85. This shows their reliability for use in a warm humid climate. Previous studies (Chen and Matzarakis, 2014; Coccolo et al., 2016; Johansson et al., 2014) have shown that PET is the most commonly used index, and the most frequently used index in warm humid climates (Binarti et al., 2020). Its strength and potential in this context could be accounted for by its standard clothing and activity being similar to those found in this climate (Fang et al., 2018; Johansson et al., 2018; Li et al., 2016a). Higher correlations of SET* to MTPV observed in this study (R^2 = 0.95) was similarly noted in other studies (Johansson et al., 2018; Zhao et al., 2016). It is argued that the better correlation to MTPV is due to the inclusion of the clothing and activity calculation in SET* (Zhao et al., 2016).

The results presented here showed that, at higher temperatures, MTPV decreases as index temperature increases for both PET and UTCI. The same trend has been observed in other studies, such as Fang et al. (2019) in humid subtropical Guangzhou, China, and Elnabawi et al. (2016) in hot arid Cairo, Egypt. Fang et al. (2019) argue that, at higher index temperatures, the actual thermal responses of respondents exceed the heat stress limits, and the respondents have no other choice but to choose the highest level of heat stress.

6.2 Urban design measures to improve thermal comfort

6.2.1 Influence of trees with different LAI

The study showed that adding trees with LAI of 2, 4, and 6 within the existing informal urban fabric considerably improves the microclimate and outdoor thermal comfort. Addition of trees not only provides shade and alters T_a and air humidity by transpiration (Bowler et al., 2010), but also reduces the surface temperature of the surrounding shaded surfaces (Akbari et al., 2001). The results show a substantial reduction of T_{mrt}, which in turn leads to a reduction of the PET. For example, dense trees with LAI of 6 have a potential to reduce T_{mrt} from 51.5°C to the neutral T_{mrt} of 32°C (Paper III) at 14:00.

On the other hand, adding trees did not produce a considerable change in T_a (see Fig. 6a in Paper IV). A marginal difference (0.2°C) was observed between 12:00 and 15:00. A similar trend was observed by Zheng et al. (2018), but in their study the reduction of T_a was much higher (0.63-1.46°C). Similarly, other studies such as Bowler et al. (2010), Cohen et al. (2012) and Papadakis et al. (2001) have shown that the cooling effect of trees is considerably larger on surface temperatures than on T_a. Under a tree the reduction of radiative fluxes by canopy shading is substantial (Mahmoud, 2011), but T_a around the location may not show much difference due to air turbulence within short distances (Lin et al., 2017).

It is worth noting that the informal urban fabric has limited adaptive options, e.g. street canopies and trees for shade (Paper III). Adding trees plays an important role in improving the microclimate and thermal comfort condition of the residents. However, it was not possible to reach thermally acceptable limits, because the day of analysis was considerably warmer than normal in March.

6.2.2 Influence of building height

Incremental increase of the building height did not result in considerable changes of T_a, as the maximum reduction was found to be 0.25°C (Paper IV). This weak relationship between changing H/W ratio and T_a was also noted in several other studies, e.g. Andreou and Axarli (2012). An explanation for this trend is that T_a distribution is not only affected by urban geometry but also by the combined effect of surface characteristics and air mixing rate (Santamouris, 2001). In warm humid climates, the sensitivity of respondents to a small decrease in T_a is noted in studies such as Baruti et al. (2020) and Villadiego and Velay-Dabat (2014); however, it is not easy to ascertain the impact of the 0.25°C decrease on the residents.

An incremental increase of building height shows considerable improvement of T_{mrt} within the urban canyon at 14:00, up to 11.2°C for the height of 24 m (Paper IV, Fig. 10b). It is worth noting that low-rise building areas receive high amounts of solar radiation. Modifying the urban fabric by increasing building heights therefore substantially reduces T_{mrt} and improves outdoor microclimate. In their studies in warm humid climates, Emmanuel and Johansson (2006), Kakon et al. (2009) have shown that an increase in building height considerably reduces T_{mrt}. Although an increase in building height shows significant reduction in T_{mrt}, it is difficult to reach neutral T_{mrt}, which was found to be 37°C (Baruti et al., 2020). This is because an increase in building height alone cannot provide effective shade in areas close to the Equator due to the high solar elevation at noon (Yahia et al., 2018).

With regard to outdoor thermal comfort, the increase of building height also substantially reduces PET. However, it has to be noted that in the tropical context with overhead sun, the effectiveness of the shade is reduced at the peak time from 11:00 to 14:00, as the sun is overhead. A reduction of PET of up to 3.8°C can be achieved by increasing building heights to 24 m, but this is 5°C PET short of the acceptable thermal limits of 32.2°C PET, as shown in Paper III. However, it should be noted that the studied day was considerably warmer. Due to the nature of development and plot sizes in informal settlements (small and compact development), it is not realistic to increase building height to 24 m, so the addition of trees becomes necessary.

6.2.3 Influence of combining building height and trees

This study found further improvement in terms of reduction of T_{mrt} by combining an increase of building height with the addition of trees. A decrease of T_{mrt} up to 15.1°C was noted at the building height of 24 m and trees with LAI 6. Consequently, it was possible to reach the neutral T_{mrt} of 32°C through these improvement measures of combining height and vegetation (Paper IV). Further analysis reveals that the combination of changing height of buildings and addition of trees substantially reduces T_{mrt}, which demonstrates the importance of trees within urban canopy layers (Ndetto and Matzarakis, 2013b; Yahia et al., 2018).

It was noted that a combination of increased building height and trees brings about the maximum reduction of PET. Although it is not possible to reach thermally acceptable limits during the warmest month, substantial improvement was achieved. For building heights 12 m and 24 m with LAI 6, a reduction of PET ranging from 5.0-6.2°C, and 5.2-6.4°C respectively was observed from 10:00-4:00 (Paper IV). Yahia et al. (2018) noted that further addition of trees can reduce PET up to 14°C. Further analysis reveals that trees have the highest ultimate effect on reducing PET (Paper IV).

7 Conclusions and recommendations

In this chapter conclusions and recommendations based on the findings are presented. The chapter highlights the contribution of the study to knowledge in the fields of urban microclimate and thermal comfort in informal urban areas. The conclusions are divided into two parts: thermal perception of the urbanites, and urban design measures for improving thermal comfort. The recommendations are intended for both practitioners and policy makers.

7.1 Conclusions

7.1.1 Urbanites' thermal perception

One major area of focus for this research was urbanites' thermal perception of the outdoor environment in informal urban areas. The influence of individual microclimate variables on thermal perception, thermal comfort limits, thermal neutrality, and thermal preference was assessed to gain an understanding of thermal experiences of urbanites in these areas. It can be concluded that:

- Among the microclimatic variables, air temperature (T_a), mean radiant temperature (T_{mrt}), and vapour pressure have a strong influence on urbanites' thermal perception. Air humidity is one of the important microclimate variables – a considerable difference in vapour pressure between seasons (high vapour pressure in the wet season and lower vapour pressure in the dry season) is what defines the dry (cool) and wet (warm) seasons.
- Adaptive options play a great role in coping with thermal discomfort conditions. From this research, it can be concluded that

residents in informal settlements have limited adaptive options, which amplifies thermal discomfort conditions.

- The studied informal settlements present a narrow thermal comfort range, and during the warmest hours of the day (11:00-16:00), the majority of urbanites' thermal perception votes are above that range. Urbanites in informal settlements have limited adaptive options, which compels them to have higher thermal tolerance. Neutral index temperatures were considerably higher than preferred index temperatures, indicating that urbanites in informal settlements want lower index temperatures.
- Urbanites in informal settlements were found to have a conservative dressing code, with relatively high clo level regardless of the season. This could be because the majority of the respondents live and work in the same areas, and also because annual variations on T_a are small.
- The rational indices, physiological equivalent temperature (PET), new standard effective temperature (SET*), and universal thermal climate index (UTCI), all performed well. Statistically, the UTCI index showed the strongest correlation, especially in the wet (warm) season, followed by SET*.

7.1.2 Urban design measures for improving thermal comfort

Another area of focus for this research was the influence of urban design measures, such as increased building heights and adding trees with different leaf area index (LAI), on both microclimate and outdoor thermal comfort. Both an increase in tree LAI and incremental increase of building height considerably improves the thermal comfort, by reducing T_{mrt} and PET. It can be concluded that:

- The effectiveness of the shade from the increase in building height is limited specifically to the warmest hours of the day (11:00-16:00) when the solar angle is high (overhead sun) due to the closeness to the Equator. It is difficult to reach neutral T_{mrt} (see Section 5.1.1) in the wet season through this urban design measure alone. Changing the building heights in informal settlements has insignificant influence on reducing T_{mrt}.
- Trees can reduce T_{mrt} and PET due to their potential to reduce the impact of solar radiation, especially for high LAI. Addition of trees has a particularly strong influence around midday because

of their capacity for solar radiation attenuation, which outweighs the limited amount of shadow cast by buildings at high solar elevation angles.

- The combination of increasing building height and adding trees results in the maximum reduction of both T_{mrt} and PET. This is the only measure that can reduce T_{mrt} to the neutral T_{mrt} (32°C) in the challenging thermal conditions of the wet (warm) season.

7.2 Recommendations to practitioners and policy makers

Practitioners urgently need knowledge on the subjects of outdoor thermal comfort and urban climate, and on how to analyse the built and planned/designed urban environment. This can be achieved through interactive cooperation between practitioners and universities in addressing those areas through programmes tailored for practitioners. Universities can play a role of capacity building by developing special courses to cater for the needs of various institutions involved in development of informal settlements. Any approach to upgrading informal settlements has to consider the issue of outdoor thermal comfort. Achieving better outdoor thermal environments in these settlements requires a participatory approach for all key stakeholders involved in upgrading processes, such as planners, architects, urban designers, and communities residing in these areas.

Upgrading proposals for informal settlements should consider aspects such as trends of densification and intensification to improve outdoor microclimate, as well as adaptive options such as addition of trees and/ or artificial shading devices. Practitioners also need tools to analyse the outdoor thermal environment. Software for analysis of the outdoor thermal environment as well as micro-meteorological measurement tools can be a basis of analysing the present conditions of informal settlements, and, furthermore, predict the future conditions for upgrading purposes.

Policy makers, for their part, need to be aware of the consequences of poor outdoor microclimate, which produces outdoor thermal discomfort conditions. Thermal discomfort conditions in informal settlements lower the quality of life, reduce the possibility for urbanites to cope with episodes of hot weather, and increase heat-related illness. Similarly, it is crucial for policy makers to be aware that a thermally comfortable outdoor environment allows all-year use of the outdoor environment, which has both social and economic benefits. Policies such as the 1995 National Land Policy and the 2000 National Human Settlements Development Policy prohibit the removal of informal settlements, and reinforce the commitment of the government on upgrading them (URT, 1995, 2000). However, this commitment is limited in terms of providing basic infrastructures. None of these policies address the issue of improvement of outdoor microclimate and outdoor thermal comfort in these settlements. Formulation of policies that address outdoor microclimate could guide the practice through regulation. For example, regulation on densification of these informal settlements must Outdoor thermal comfort of residents in a warm humid climate must be formulated on the basis of analysis of impact of densification on the outdoor thermal environment

8 Further research

One area for further study is a comparative analysis of urbanites' thermal perception, between those residing in formal and informal settlements in a warm humid climate for both the dry (cool) and wet (warm) seasons. The study can bring an insight into the differences as regards thermal preference, neutrality and thermal comfort limits between residents of these settlements. Proper monitoring of the effect of microclimate conditions of the location and thermal perception of urbanites requires both meteorological measurements and survey questionnaires, conducted simultaneously in both formal and informal settlements, and has to involve a standard type set-up of meteorological equipment.

Among the consequences of climate change is the increase in global temperatures. For informal settlements, the implications of climate change on the lives of the urbanites residing in these settlements should be investigated. A likely consequence of climate change is that the wet season will become hotter and more unbearable and there will probably be less thermal relief during the dry season. A study in this area could further inform policy makers and practitioners on the necessary measures to be considered to reduce the negative effects of hot weather.

Another area for research is to investigate the effectiveness of different urban design measures, such as covered pedestrian streets. An investigation into urbanites' thermal experiences of being exposed to heat stress, and implications for health, is also recommended.

Further research is required to investigate different tree species in Tanzania, their speed of growth and their LAI values. There is also a need to explore the potential contribution of landscaping in informal settlements.

Summary

Informal settlements are urban areas that develop and grow without formal planning. In these settlements, climate-related environmental challenges include poor dispersion of air pollutants (due to low wind speed), poor human thermal comfort, and high level of heat stress, which reduces productivity and leads to a potential increase of heat-related illness. This study investigated how residents of informal settlements in the city of Dar es Salaam, Tanzania, perceive the outdoor thermal environment. It further explored how microclimate and outdoor thermal comfort are influenced by measures such as increased building heights and addition of trees.

Among the microclimatic variables, solar radiation, air temperature, and air humidity were found to have a strong influence on urbanites' thermal perception. Solar radiation particularly influences thermal perception during the hottest part of the day (11:00-16:00), when the majority of residents in the outdoor environment tend to seek shade. Residents showed high sensitivity to minor changes in air temperature, as a slight decrease/increase in air temperature led to substantial changes in the thermal perception. High air humidity and air temperatures observed in the wet season negatively influence residents' thermal perception, whereas a decrease in air humidity in the dry season provides relief. A significant difference in the combination of air temperature and air humidity between seasons is what defines the dry (cool) and wet (warm) seasons. Since air temperatures are moderately high in both seasons, seasonal differences in thermal perception mainly depend on the air humidity rather than temperature.

In terms of behavioural coping strategies, the study showed that the limited number of trees and structures such as arcades, verandas, and street canopies provide little shade to the residents in informal settlements. The lack of shading options, reported by 95% of respondents in a survey, amplifies thermal discomfort conditions. Residents in informal settlements were also found to have a conservative dressing code (fairly heavy clothing) regardless of the season.

During the warmest hours of the day (11:00–16:00), the majority of the urbanites perceived moderate to strong heat stress during both the wet and dry seasons. However, since most of the residents in the informal settlements do not have access to air conditioning, this compels them to have higher tolerance to warm thermal conditions. Urbanites in informal settlements were found to prefer lower temperatures.

Both an increase in tree shading capacity and incremental increase of building heights were found to considerably reduce solar radiation and improve outdoor thermal comfort in a street canyon. Increased building heights are effective in reducing the effects of solar radiation, but the effectiveness of this shade was found to be limited to the warmest hours of the day (11:00-16:00) when the solar angle is high (overhead sun) due to the closeness to the Equator. Trees have been shown to be more efficient in reducing solar radiation because of their potential to minimise the impact of overhead sun through reduction of radiative fluxes. In reducing solar radiation, trees improve outdoor microclimate, prevent strong heat stress during warm days, and improve the wellbeing of the residents in the informal settlements.

The importance of this study is related to the need to understand residents' thermal perception of the outdoor thermal environment in informal settlements and their challenges, as the outdoor thermal environment has a direct implication for residents' health and wellbeing. It can be argued that improved urban designs that optimise thermal comfort can raise the quality of life in general, as well as help urban dwellers to cope with episodes of hot weather and allowing year-long outdoor activities. If the outdoor climate is thermally comfortable, urban space use levels are more likely to increase. It is of paramount importance to equip practitioners, such as spatial planners, architects, and urban designers, with the knowledge and tools necessary for analysing microclimate and thermal comfort, and considering them in upgrades of informal settlements, urban regeneration, and urban and settlement planning. Policy makers must be informed about the consequences of poor microclimate and outdoor thermal discomfort conditions underpinned by urban transformation. This could enable them to formulate policy guidelines that can lead to proper and appropriate urban development standards that promote thermally comfortable environments.

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Appendix

Questionnaire

Outdoor Thermal Comfort Questionnaire

Place: ....
Date: ....
Time: ....

1. Personal information

Sex: ☐ Male ☐ Female

Age: ☐ ≤ 20 ☐ 21-35 ☐ 36-50 ☐ 51-65 ☐ 66-80 ☐ >80

☐ Live in the neighborhood ☐ Work in the neighborhood ☐ Neither of them

2. What is the reason for being in this place?

☐ On my road to home/work/school/etc ☐ See other people/Relax/Get fresh air
☐ Both ☐ Other reason ……………………………………………..…

3. How often do you pass by this place?

☐ Daily ☐ A few times/week ☐ A few times/month ☐ Rarely ☐ First time

4. How long time have you been outdoors today?

☐ Less than one hour ☐ Between 1-2 hours ☐ Between 2-3 hours ☐ More than 3 hours

5. How did you spend the last half hour?

☐ Sitting ☐ Standing ☐ Walking ☐ Other …………………………..

6. How do you feel in this place right now?

Cold	Cool	Slightly cool	Comfortable	Slightly warm	Warm	Hot
☐	☐	☐	☐	☐	☐	☐

7. How do you sense the climate in this place?

Temperature:	☐ Warm	☐ Neutral	☐ Cold
Sun:	☐ Sunny	☐ Neutral	☐ Shady
Humidity:	☐ Humid	☐ Neutral	☐ Dry
Wind:	☐ Windy	☐ Neutral	☐ Calm

8. How would you prefer the climate in this place?

Temperature:	☐ Warmer	☐ No change	☐ Colder
Sun:	☐ More sun	☐ No change	☐ More shade
Humidity:	☐ More humid	☐ No change	☐ Less humid
Wind:	☐ More wind	☐ No change	☐ Less wind

9. Where do you prefer to spend your free time?

☐ Indoors ☐ Outdoors ☐ Other ……………………………………………

10. What type of clothing do you wear?

Shirt	*Trousers*	*Shoes*	*Traditional*	*Head*	*Other*
☐ Short sleeves	☐ Shorts/skirt	☐ Sandals	☐ Kanzu	☐ Hat	☐ .... ……..
☐ Long sleeves	☐ Long trousers	☐ Shoes	☐ Khanga	☐ Parasol	………………..
☐ Singlet top			☐ Masai dress		

11. How do you cope with extreme outdoor weather?

Clothing	*Sitting/Walking*	*Drinking*	*Relaxing*	*Other*
☐ Change clothing	☐ On shaded areas	☐ Cold fluid	☐ Swimming	☐ .... ……..
☐ Remove clothing	☐ With Umbrella	☐ Normal fluid	☐ Fanning	………………..

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Paper I

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REVIEW PAPER

Check for updates

Review of studies on outdoor thermal comfort in warm humid climates: challenges of informal urban fabric

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Abstract
In warm humid climate regions where majority of the population spend most of the time outdoors, an adequate outdoor thermal environment is crucial. A number of studies on outdoor thermal comfort in warm humid climates were carried out in the past decade. However, most of these studies focused on the formal urban fabric and left the informal urban fabric, where typically 30 to 85% of the population in developing countries resides, unattended. Theoretically, the informal urban fabric structure of towns/cities poses many outdoor thermal environmental challenges, such as lack of air movement, high thermal stress and discomfort. This paper reviews previous research on outdoor thermal comfort in warm humid climates, and, particularly, it focuses on the relationship between outdoor thermal comfort and urban fabric as well as human thermal perception. Regarding the formal urban fabric, this review asserts that the thermal comfort range is higher in warm humid climates than in temperate climates and that thermal indices alone cannot predict thermal comfort; behavioural and psychological adaptation have proven to have a big impact on thermal perception. As for the informal urban fabric, only few studies have investigated the influence of the urban geometry and none has studied people's thermal perception of the outdoor thermal environment. To conclude, the article highlights practical challenges posed by the informal urban fabric in contrast to the formal urban fabric in terms of structure (morphology).

Keywords Outdoor thermal comfort · Warm humid climates · Thermal indices · Informal urban fabric · Informal settlements · Acceptable index temperature limits

Introduction

Outdoor thermal comfort studies are crucial for understanding people's response to their thermal environments. This understanding can set a basis for prediction of the outdoor thermal environment in urban areas. Warm humid climates are characterised by long periods of warm weather in which outdoor and semi-outdoor environments are considered more conducive than indoor environments especially when there is no air-conditioning. Contrary to cold and temperate climates, people in warm humid tropical climates, especially those in developing countries, spend more time outdoors than indoors. Thus, a pleasant outdoor thermal environment is crucial for the well-being of urban dwellers. In addition, comfortable outdoor spaces have a significant bearing on the comfort perception of the indoor ambience (Ahmed 2003).

Several studies on outdoor thermal comfort with different objectives and methods of analysis have been carried out in warm humid tropical and subtropical regions. For example, in the humid subtropical region, studies by Chen et al. (2015), Cheng et al. (2012), Hirashima et al. (2016), Hwang and Lin (2007), Hwang et al. (2010), Li et al. (2016a), Lin et al. (2013), Lin (2009), Lin et al. (2011), Lin et al. (2012a), Lin et al. (2012b), Lin and Matzarakis (2008), Liu et al. (2016), Lucchese et al. (2016), Ng and Cheng (2012), Spagnolo and de Dear (2003), Watanabe et al. (2014), Xi et al. (2012) and Yang et al. (2013b) were carried out. In the tropical rainforest region, studies by Makaremi et al. (2012), Trindade da Silva and Engel de Alvarez (2015), Yang et al. (2013a) and Yang et al. (2013b) were carried out. In the tropical savanna, there are also studies, such as those of Johansson et al. (2018), Kruger et al. (2017) and Ndetto and Matzarakis (2016). The

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above-mentioned studies are the foundation and provide perspectives on the state of outdoor thermal comfort in warm humid tropical regions, especially in formal (planned) urban areas.

Urbanization in developing countries has contributed to rapid growth of informal urban areas. According to the UN Habitat (2016), one in eight people lives in slums globally, and, in developing countries, 30% of urban residents lived in poor informal settlements in 2014. In Tanzania, Lusugga Kironde (2006) comments that recent calculations based on property tax databases, which include properties in both planned and unplanned areas, indicate that over 80% of all buildings in the city of Dar es Salaam[1] are situated in unplanned areas. Social, economic and environmental challenges facing informal urban areas occupied the research community for decades, whereas thermal comfort issues did not. Informal urban fabric structures and the outdoor thermal environment need special attention for analysis, as they are complex. According to Sobreira and Gomes (2001), the geometry of informal settlements does not consist of regularly distributed dwellings; in fact, they display a complex structure. In addition, parameters normally used to study the physical properties of the urban canopy layer in the formal urban fabric, such as height-to-width (H/W) ratio of streets, and street orientation might not directly apply in the majority of the informal urban fabrics.

The influence of the urban fabric on microclimate and outdoor thermal comfort in the warm humid tropical and subtropical regions is reported by several studies. In the humid subtropical regions, for example, studies by Assis and Frota (1999), Johansson et al. (2013), Kakon et al. (2009), Kakon et al. (2010), Lin et al. (2010), Sharmin et al. (2015), Tan et al. (2017), Yang et al. (2011) and Yang and Lin (2016) are available. In the tropical rainforest regions, examples of studies include those of Emmanuel and Johansson (2006), Emmanuel et al. (2007), Johansson and Emmanuel (2006) and Qaid and Ossen (2015), and, in the tropical savannah regions, studies of De and Mukherjee (2018), Ndetto and Matzarakis (2013), Rodríguez-Algeciras et al. (2016) and Yahia et al. (2018) exist. Most of these studies investigate the formal urban fabric of the cities characterised by a designed and coordinated pattern of streets that are different from the informal urban fabric. In addition, these studies found differences in terms of microclimate and outdoor thermal comfort between low-rise and high-rise building areas in the formal urban fabric context.

Regarding outdoor thermal comfort, studies of Chen and Ng (2012), Nikolopoulou (2011), Potchter et al. (2018) and Vanos et al. (2010) were carried out, and they focus on different aspects. For example, Vanos et al. (2010) focused on the physiology of human thermal comfort while exercising. On the other hand, Nikolopoulou (2011) focused on thermal adaptation and approaches in understanding outdoor thermal comfort; Chen and Ng (2012) focused on the behavioural aspects of outdoor thermal comfort and Potchter et al. (2018) focused on approaches, methods and quantification of outdoor thermal perception in various climates.

This paper presents a review of studies on outdoor thermal comfort in warm humid tropical regions focusing on two major parts. The first part presents a review of outdoor thermal comfort studies based on a subjective assessment of the thermal environment using field surveys. The second part presents a review of studies, which focuses on the relationship between the urban fabric and measured or calculated outdoor thermal comfort. Subsequently, the review presents a general perspective of outdoor thermal comfort in warm humid climates and outlines challenges of the informal urban fabric. Although previous studies show that urban geometry is one of the key determinants of outdoor microclimate and consequently human thermal comfort, other studies show that the latter is more complex due to psychological and behavioural factors (Nikolopoulou 2011; Nikolopoulou and Steemers 2003). The assumption that findings in the formal urban fabric can be applicable in the informal urban fabric can lead to lack of interest to investigate the thermal environment and people's thermal perception of the latter. Knowledge on people's thermal perception in the informal urban fabric is necessary to inform urban designers and planners who are involved in upgrading of the informal urban fabric. In addition, understanding of coping strategies, thermal neutrality and thermal preference and acceptable comfortable ranges is necessary for understanding of the thermal environment in these places.

The review is limited to warm humid climates, and it sets the basis to point out the research gap for further studies. It focuses on the following Köppen groups by Kottek et al. (2006): the equatorial zone (A), which is often referred to as tropical, e.g. tropical savannah (Aw) and tropical rainforest (Af) as well as the warm temperate zone (C), e.g. humid subtropical (Cfa) and monsoon-influenced humid subtropical (Cwa). The study has excluded hot summer and warm-summer Mediterranean climates (Csa and Csb). In addition, this review is limited to international peer-reviewed articles in the English language.

Field studies on outdoor thermal comfort in warm-humid climates

Table 1 presents a list of studies reviewed in this section. Since one of the aims of Table 1 is to compare results from different sub-climates of warm humid tropical climates, studies that used PET are listed first as they are the majority. All studies reviewed in this section include fieldwork in outdoor or semi-outdoor environments consisting of simultaneous

[1] Commercial capital and largest city of Tanzania in East Africa.

Table 1 Review of outdoor thermal comfort studies in warm humid tropical climates. Thermal indices: PET, physiologically equivalent temperature; SET* (OUT_SET*), standard effective temperature; UTCI, universal thermal climate index; ETU, universal effective temperature; ET*, effective temperature; PT, perceived temperature; TOP, operative temperature; WBGT, wet bulb globe temperature; T_a, air temperature (T_a is not a thermal index but has been used in some studies)

	City, country	Source	Thermal indices	Neutral index temperature (°C)			Preferred index temperature (°C)			Acceptable index temperature ranges (°C)		
				Winter/ cool	Summer/ warm	All year	Winter/ cool	Summer/ warm	All year	Winter/ cool	Summer/ warm	All year
A	Tropical savanna (Aw)											
1	Dar es Salaam, Tanzania	Ndetto and Matzarakis (2016)	PET	–	27	–	–	–	–	–	23.0–31.0	–
2	Guayaquil, Ecuador	Johansson et al. (2018)	PET	21.9	26.9	25.7	15.5	18.6	17.5	Upper 34.3	Upper 25.3	Upper 31.3
			SET*	20.5	24.5	24.3	17.7	23.3	18.6	Upper 30.9	Upper 25.3	Upper 29.0
3	Rio de Janeiro, Brazil	Kruger et al. (2017)	PET	–	–	–	–			–		
			UTCI	–	–	–	–			–		
B	Tropical rainforest (Af)											
1	Singapore	Yang et al. (2013b)	PET	–	–	28.1	–	–	25.2	–	–	24.0–30.0
2	Vitoria, Brazil	Trindade da Silva and Engel de Alvarez (2015)	PET	–	–	–	–	–	–	–	–	22.0–30.0
3	Singapore	Yang et al. (2013b)	PET	–	–	28.7	–	–	26.5	–	–	26.3–31.7
4	Putra, Malaysia	Makaremi et al. (2012)	PET	–	–	–	–			–		
C	Humid subtropical (Cfa and Cwa)											
1	Changsha, China	Yang et al. (2013b)	PET	–	–	27.9	–	–	22.1	–	–	24.0–31.0
2	Changsha, China	Liu et al. (2016)	PET	14.9	23.3	18.2	–	–	–	–	–	15.0–22.0
3	Shanghai, China	Chen et al. (2015)	PET	22.4			–	–		15.0–29.0		
4	Guangzhou, China	Li et al. (2016a, 2016b)	PET	15.6			–	–		18.1–31.1		
5	Sydney, Australia	Spagnolo and de Dear (2003)	PET				–	–		21.5–32.4	–	
6	Hong Kong	Cheng et al. (2012)	PET	20.7	25.0		–	–				19.0–30.0
7	Sun Moon Lake, Taiwan	Lin and Matzarakis (2008)	PET			27.2						26.0–30.0
8	Taichung, Taiwan	Lin (2009)	PET	23.7	25.6		23.0	24.5				21.3–28.5
9	Campo Grande, Brazil	Lucchese et al. (2016)	PET							21–27		
10	Yunlin, Taiwan	Lin et al. (2012)	PET									21.3–28.5
11	Hong Kong	Ng and Cheng (2012)	PET		28.1					14–16	27.0–29.0	
12	Chiayi, Taiwan	Lin et al. (2012a, 2012b)	PET								26.1–30.4	
13	Belo Horizonte, Brazil	Hirashima et al. (2016)	PET	15.9	27.7		20.9	14.9				19.0–27.0
14	Chengdu, China	Zeng and Dong (2015)	PET	–	24.4	–	–	–	–	–	20.0–29.5	–
15	Hong, Kong	Huang et al. (2017)	PET			20.7						16.4–25.2
			UTCI			22.7						18.9–26.5
16	Taichung, Taiwan	Hwang et al. (2010)	TOP	22.8	28.2							19.0–31.8
17	Taichung, Yunlin, Chiayi, Taiwan	Lin et al. (2011)	SET*	28	29.3		26.7	28.5				
18	Taichung, Taiwan	Hwang and Lin (2007)	SET*			27.2			26.9			19.7–34.7
19	Taichung, Taiwan	Lin et al. (2013)	WBGT			23.2						20.0–26.0
20	Guangzhou, China	Xi et al. (2012)	SET*		24.0							
21	Nagoya, Japan	Watanabe et al. (2014)	ETU		33.1							
			SET*		34.0							
			UTCI		28.9							
22	Dhaka, Bangladesh	Ahmed (2003)	T_a	–	–	–	–			–		

micrometeorological measurements and assessment of subjective thermal perception of people. Subjective thermal comfort data were recorded using questionnaires with questions on the thermal state of the subjects. Measurements included the four basic environmental parameters with an influence on thermal comfort, namely, air temperature, humidity and radiation, for calculation of the mean radiant temperature (MRT)[2] and wind speed. The thermal comfort indices used in these studies are divided into two groups based on Blazejczyk et al.'s (2012) simple indices, i.e. operative temperature (TOP)[3] and wet bulb globe temperature (WBGT).[4] Indices based on heat budget models, i.e. physiologically equivalent temperature (PET),[5] new effective temperature (ET*),[6] standard effective temperature (SET*)[7], sometimes referred to as OUT_SET* when used outdoors, universal thermal climate index (UTCI)[8] and perceived temperature (PT),[9] were used. Detailed descriptions of these indices are found in Blazejczyk et al. (2012), Johansson (2016) and Johansson et al. (2014).

Thermal comfort is defined as "that condition of mind which expresses satisfaction with the thermal environment" (ASHRAE 2004; Fanger 1972; ISO 2005) and no preference to be warmer or cooler (Fanger 1972). The concept of thermal comfort in outdoor environments is more complex than that in indoors as it encompasses large temporal and spatial variations (Johansson et al. 2018; Nikolopoulou et al. 2001) coupled with a great range of activities people are engaged in (Nikolopoulou et al. 2001). From the beginning of the last decade, several studies (Ahmed 2003; Hwang and Lin 2007; Lin 2009; Lin and Matzarakis 2008; Spagnolo and de Dear 2003) have focused on the causal linkage between biophysical environments and the subject's state of thermal comfort in warm humid climates. In these studies, different thermal indices were applied; some of the studies (Huang et al. 2017; Johansson et al. 2018; Kruger et al. 2017; Spagnolo and de Dear 2003; Watanabe et al. 2014) compared more than one index. In addition, some studies (Ahmed 2003; Villadiego and Velay-Dabat 2014; Yin et al. 2012) did not use commonly known thermal indices; instead, air temperature was considered in the evaluation of the outdoor thermal comfort. It is worth to note that majority of studies carried out in warm humid tropical climates used at least one of the common thermal indices to evaluate respondents' thermal perception (Table 1).

Furthermore, different studies have investigated both respondents' thermal neutrality and preference. Some studies (Chen et al. 2015; Cheng et al. 2012; Huang et al. 2017; Hwang et al. 2010; Li et al. 2016a; Lin et al. 2013; Lin and Matzarakis 2008; Liu et al. 2016; Ndetto and Matzarakis 2016; Ng and Cheng 2012; Watanabe et al. 2014; Xi et al. 2012; Zeng and Dong 2015) investigated only thermal neutrality. Other studies (Hirashima et al. 2016; Hwang and Lin 2007; Johansson et al. 2018; Lin 2009; Lin et al. 2011; Spagnolo and de Dear 2003; Yang et al. 2013a) investigated both neutral and preferred temperature. In addition, majority of these studies determined thermally acceptable ranges for the outdoor environment in warm humid climates.

Thermal neutrality

The neutral temperature (T_n) is defined as the index temperature at which 50% of the sample voted "cooler than neutral" and 50% voted "warmer than neutral" (Spagnolo and de Dear 2003). Studies (Lin 2009; Liu et al. 2016; Spagnolo and de Dear 2003) have found significant differences in thermal neutrality between seasons in warm humid climates. Neutral temperature variations between seasons observed in studies, which used PET as thermal index for winter and summer, respectively, are as indicated in Table 1. Subsequently, studies by Hirashima et al. (2016), Hwang et al. (2010), Johansson et al. (2018), Lin (2009), Lin et al. (2011) and Liu et al. (2016) compared neutral temperatures for two seasons and found that people had different thermal perception in each season. In the winter season, the neutral temperature was lower compared to that in the summer season. This shows that adaptation influences outdoor thermal comfort; thus, people in Taiwan have more tolerance to high temperature than lower temperature as they experience high temperature for a longer period of the year. The marginal difference in the neutral temperatures between hot and cool seasons is associated with the effect of seasonal adaptation on thermal comfort as a result of psychological and behavioural adaptation to variations in microclimate (Lin et al. 2011). On the same note, Hwang et al. (2010) found a variation of 6 °C between winter (22.8 °C) and summer (28.2 °C) of neutral operative temperature (TOP) for respondents in Taichung, Taiwan. In addition, the study noticed that the neutral operative temperature follows the profile of the respective monthly mean air temperature. The findings confirm the relationship between mean monthly outdoor

[2] The uniform surface temperature of an imaginary black enclosure with which man (also assumed black body) exchanges the same heat by radiation as in the actual environment.

[3] This is an arithmetic average of MRT and T_a into a single index.

[4] A heat stress index calculated from dry-bulb temperature, wet-bulb temperature and black globe temperature.

[5] Thermal comfort index representing the air temperature of a standard indoor environment in which a person with standard indoor activity and clothing has the same skin and core temperature as in the actual outdoor environment.

[6] Thermal comfort index that represents the temperature of a standard environment in which a subject would experience the same skin wettedness and skin temperature as in the actual environment.

[7] Thermal comfort index that represents the temperature of a standard environment at 50% relative humidity for respondents wearing clothing standardized for the given activity in the real environment.

[8] Thermal comfort index representing the air temperature of a reference environment, which provides the same physiological response of a reference person as the actual environment.

[9] Thermal comfort index expressed as the air temperature in a standardised environment, which achieves the same predicted mean vote, PMV, as the real environment.

temperature and neutral air temperature, which was applied to develop the adaptive comfort model.

On the other hand, studies by Johansson et al. (2018) and Spagnolo and de Dear (2003) observed neutral temperature in the cool season being higher than in the warm season. In humid subtropical Sydney, this was associated with the fact that respondents ignored the warmth contributed by the winter clothing (Spagnolo and de Dear 2003). In the tropical savanna climate of Guayaquil, voting may be based on previous experience. That is, people were so tired of the uncomfortable thermal conditions of the wet (warm) season that they gave higher thermal perception votes than they did at similar thermal conditions during the dry (cool) season (Johansson et al. 2018).

Other studies (Huang et al. 2017; Hwang and Lin 2007; Spagnolo and de Dear 2003; Zhang et al. 2018) conducted a comparative analysis of thermal environment conditions between outdoor, indoor and semi-outdoor. Some of them found that the neutral standard effective temperature (SET*) in outdoor environments significantly exceeds the recommended value for indoor environments (Hwang and Lin 2007; Spagnolo and de Dear 2003). Hwang and Lin (2007) found higher levels of neutral temperature in comparatively warmer environments which supports the occurrence of thermal adaptation among respondents of semi-outdoor and outdoor environments. The neutral temperature for indoor, semi-outdoor and outdoor environments was 24.4, 25.8 and 27.2 °C SET*, respectively. The variation of thermal neutrality between the two spaces reinforces the argument that spatial and temporal variations of microclimate present different thermal conditions and adaptation possibilities. Contrary to the previous studies, Zhang et al. (2018) found higher neutral temperatures indoors than in semi-outdoor areas in the rural areas of Guangdong, China. Neutral temperatures in indoor spaces were 24.0 and 19.7 °C TOP in the warm and cool seasons, respectively. For semi-outdoor areas, neutral temperatures were 23.4 and 18.4 °C TOP in the warm and cool seasons, respectively.

Thermal preference

Preferred temperature is the temperature that people want (Lin 2009). In theory, preferred temperature depicts expectation of the respondents from the thermal environment they experience. In studies by Johansson et al. (2018), Lin et al. (2011) and Yang et al. (2013a), preferred temperatures were found to be lower than neutral temperature demonstrating the influence of expectation. This is true for outdoors, semi-outdoors and indoors. Hwang and Lin (2007) noticed that the preferred temperatures for both outdoors (26.9 °C SET*) and semi-outdoors (24.6 °C SET*) were 1.2 and 0.3 °C lower than the neutral temperature for outdoors and semi-outdoors, respectively. There are also seasonal differences. Lin (2009) found that preferred PET in both cool and hot seasons were slightly lower than the neutral temperature and the percentage of those who “prefer cooler” in the hot season is greater than that in the cool season for high SET* bins of 34–39 °C. This is due to the fact that the air temperature is higher in warm seasons (Lin et al. 2011). In one study in Belo Horizonte, Brazil, Hirashima et al. (2016) found the preferred temperature for winter and summer to be 20.9 and 14.9 °C, respectively. The study observed that preferred temperature of 14.9 °C for summer is due to the sharp drop in the number of people wanting warmer conditions in hot season with the increase of the PET.

Thermal acceptable ranges

The ASHRAE Standard 55 defines that the thermal comfort range is the temperature range that is acceptable to at least 80% (normal condition) or 90% (strict condition) of people; that is, only 10% of users feel that this thermal comfort range is unacceptable (ASHRAE 2004). Thermally acceptable ranges in warm humid tropical climates bring into attention several observations. First, several studies (Johansson et al. 2018; Li et al. 2016a; Lin 2009; Lin et al. 2012b; Lin and Matzarakis 2008; Ndetto and Matzarakis 2016; Ng and Cheng 2012) found that the thermal acceptable ranges in these regions are higher compared to those in cold and temperate climate. In the study by Lin and Matzarakis (2008) in Sun Moon Lake, Taiwan, it was found that the thermal comfort range for 80% acceptability to be 21.6–35.4 °C PET. In other studies in warm humid tropical climates, using the same thermal index, PET, similar results of high thermally acceptable ranges were found as indicated in Table 1. The comfort ranges are considerably higher compared to those in Glasgow in northern Europe where Kruger et al. (2013) found a range of 9–18 °C PET and in the Mediterranean coastal climate where Cohen et al. (2013) found a range of 20–25 °C PET.

Several studies (Johansson et al. 2014; Knez and Thorsson 2006; Li et al. 2016a; Lin 2009; Lucchese et al. 2016) have also pointed out that people in different regions have different thermal requirements due to thermal adaptation. A comparative study (Makaremi et al. 2012) of local and international students in Putra, Malaysia, reveals that local respondents could feel comfortable at much higher PET values than the international students as adaptation, both psychological and physiological, plays significant role on outdoor thermal comfort. These findings reinforce the conclusion that culture and environmental attitude play a key role in influencing thermal perception and reinforce the need to link thermal comfort indices and emotional perception of the thermal environment (Knez and Thorsson 2008).

In addition, a comparative analysis of the sub-climates within the warm humid tropical climates, e.g. tropical savannah (Aw), humid subtropical (Cfa and Cwa) and tropical rainforest (Af), reveals that the humid subtropical climate has both comfort ranges of higher PET values and wider thermal comfort ranges than the rest (Table 2). This is brought about by the nature of each sub-climate. Both the tropical savannah and tropical rainforest climates have small variations in monthly average air temperature, whereas the humid subtropical climate has distinctly different warm and cold seasons. It is likely that the higher average monthly temperatures of Dar es Salaam explain the higher thermal comfort values of 23–31 °C PET (Ndetto and Matzarakis 2016) compared to Belo Horizonte's 19–27 °C PET (Hirashima et al. 2016). Subtropical climate (Cfa) studies which involved more than one season of the year have the widest thermally acceptable ranges, for example Li et al. (2016a) in Guangzhou with 14–28 °C, Chen et al. (2015) in Shanghai with 4–28 °C and Cheng et al. (2012)in Hong Kong with 16–29 °C.

Adaptation to the thermal environment

Adaptation is defined as "the gradual decrease of the organism's response to the repeated exposure to a stimulus" (Nikolopoulou 2011). It can be physiological, behavioural and psychological. Different types of adaptation may occur simultaneously (Ng and Cheng 2012). Behavioural adaptation is a type of adjustment to the environment, which includes change of clothing, activity level, posture, moving in space and diet. Results from the reviewed field studies demonstrate that individuals change clothing levels so as to achieve comfort and that a correlation exists between clothing and thermal index value (Lin et al. 2013; Lin 2009). In addition, studies show that there are notable differences within different warm humid tropical climates when it comes to clothing. In humid subtropical climates (Cfa), studies (Hwang et al. 2010; Lin et al. 2011, 2012b) show significant differences in clothing values associated with seasonal variations, where clothing insulation increased with decreasing temperature and vice versa. Contrary to the humid subtropical climate (Cfa), in tropical savanna (Aw) and tropical rainforest (Af), climate studies (Johansson et al. 2018; Makaremi et al. 2012; Ndetto and Matzarakis 2016) show that there were no differences in clothing values in different seasons of the year. These findings can be linked to the nature of the climate. The humid subtropical climate has pronounced summer and winter seasons whereas the tropical savannah and the tropical rainforest climates have no winter, but rather wet and dry periods, and annual temperature variations are small.

Other examples of adaptive behaviour include the tendency of people to move to shaded areas or to use umbrellas (Johansson et al. 2018; Li et al. 2016a; Tung et al. 2014; Watanabe and Ishii 2016; Yang et al. 2013a). This tendency involves seeking shade under trees or man-made shading devices (Johansson et al. 2018; Lin et al. 2013, 2012b). In humid subtropical Guangzhou, Li et al. (2016a, b) found that in spring, the residents preferred activity in the border space of sunlight and shade and in summer, the residents preferred activity in the sunshade. Also, Yang et al. (2013a, b) found that moving to shaded areas, such as trees/shelters, was preferred by 80.8% of the respondents followed by the use of umbrella which was preferred by 32.5%. On studying gender differences in response to the outdoor thermal environment, Tung et al. (2014) noticed that both genders preferred moving to shaded areas as a primary adaptation method. Additionally, men preferred drinking a beverage while women preferred using an umbrella to release heat stress.

Table 2 A comparison of acceptable comfort ranges in sub-climates of warm humid climates based on PET

	City, Country	Source	Acceptable index temperature ranges (°C)			PET (°C)
			Winter	Summer	All year	14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32
A	TROPICAL SAVANNA (Aw)					
1	Dar es Salaam, Tanzania	Ndetto and Matzarakis,2016	-	23.0–31.0	-	
2	Guayaquil, Equador	Johansson et al., 2018	Upper 34.3	Upper 25.3	Upper 31.3	
B	TROPICAL RAINFOREST (Af)					
1	Singapore	Yang et al., 2013b	-	-	24.0–30.0	
2	Vitoria, Brazil	da Silva and de Alvarez, 2015	-	-	22.0–30.0	
3	Singapore	Yang et al., 2013b	-	-	26.3–31.7	
C	HUMID SUBTROPICAL (Cfa & Cwa)					
1	Changsha, China	Yang et al., 2013b	-	-	24.0–31.0	
2	Changsha, China	Liu et al., 2016	-	-	15.0–22.0	
3	Shanghai, China	Chen et al., 2015	15.0–29.0	-		
4	Guangzhou, China	Li et al., 2016	18.1–31.1	-		
5	Sydney, Australia	Spagnolo and de Dear, 2003	21.5–32.4	-		
6	Hong Kong	Cheng et al., 2012	-	-	19.0–30.0	
7	Sun Moon Lake, Taiwan	Lin and Matzarakis, 2008	-	-	26.0–30.0	
8	Taichung, Taiwan	Lin, 2009	-	-	21.3–28.5	
9	Campo Grande, Brazil	Lucchese et al., 2016	21–27			
10	Yunlin, Taiwan	Lin et al., 2012			21.3–28.5	
11	Hong Kong	Ng and Cheng, 2012	14–16	27.0–29.0		
12	Chiayi, Taiwan	Lin et al., 2012	-	26.1–30.4		
13	Belo Horizonte, Brazil	Hirashima et al, 2016	-		19.0–27.0	
14	Chengdu, China	Zeng and Dong, 2015	-	20.0–29.5	-	
15	Hong, Kong	Huang et al., 2017			16.4–25.2	
	LEGEND					LOWER LIMIT · UPPER LIMIT · COMFORT ZONE

Psychological factors, such as past experience, expectations and autonomy, are believed to have a major impact on the thermal perception and may to a large extent explain the poor correlation between the thermal perception predicted by thermal indices and subjectively perceived thermal comfort (Nikolopoulou 2011; Nikolopoulou and Steemers 2003). It is worth to note that several studies (Ahmed 2003; Makaremi et al. 2012; Zeng and Dong 2015) have shown that the thermal history, which refers to the climate a person has experienced before entering the actual climate, influences the perception of the thermal environment. Thermal history can be everything from seasonal to only a few hours but can significantly affect respondent's perception of the thermal environment. It is observed in many studies that the length of time respondents spend outdoors is one of the important factors of adaptation. Ahmed (2003) noticed that the longer the people stay outdoors the higher their comfort range when compared to those who stay for a short period of time, and, thus, respondents who were exposed to outdoor environments with longer exposure were more comfortable. Conversely, Yang et al. (2013a) found that the time of exposure did not significantly affect the thermal sensation votes.

Autonomy, which means the degree of personal control, has been found to have a considerable impact on thermal perception in warm humid tropical environments. Lin et al. (2012a, b) discovered that when the interviewee possessed autonomy (that is, they could enter or leave the park freely), they attended activities in the plaza with superior tolerance of the thermal environment, even under uncomfortable conditions. This may be attributed to the presence of numerous choices of activities, a necessary factor for adaptation. Furthermore, Lin et al. (2013) observed that when people engage in outdoor leisure activities and can freely control the time, location and type of activities, they are more able to accept the conditions of the outdoor thermal environment. Johansson et al. (2018) found acceptance of higher values of SET* (31 °C) for respondents who were voluntary in a place when compared to those who were just passing by (28 °C). In contrast, Yang et al. (2013a) found that influence of the purpose of stay on the thermal sensation of respondents in the outdoor environment was insignificant.

Influence of the formal urban fabric on outdoor thermal comfort

As pointed out by Erell et al. (2010), despite the heterogeneity of the urban canopy in any real city, it is useful to describe the fabric of buildings and open spaces in terms of quantifiable measures that express its density or other physical properties that influence the micro-scale climate. The urban fabric reflects the morphological composition of physical elements within a certain area. It can be defined by indicators such as density, compactness, variation, fragment and cohesion (Li et al. 2016b). In order to analyse the urban fabric and its influence on the outdoor thermal comfort, there is a need for an understanding of urban fabric descriptors at street level (urban canopy layer), which includes height-to-width (H/W) ratio, canyon axis orientation and sky-view factor (SVF). The mentioned urban fabric descriptors form the basis of discussion and analysis of outdoor thermal comfort at the urban level. Table 3 presents a summary of quantitative and qualitative results based on studies on the influence of the urban fabric on microclimate and outdoor thermal comfort.

Influence of microclimatic variables on thermal perception

A number of studies have investigated the influence of different microclimatic variables on thermal perception of people in warm humid climates. Results have shown that microclimatic variables vary in influence in different seasons and especially solar radiation, wind speed and air temperature have significant influence on thermal perception of people. Seasonality and the type of sub-climate within warm humid tropical climates can determine the influence of each variable.

Solar radiation

In warm humid tropical climates, studies (Hwang and Lin 2007; Lin 2009; Lin et al. 2011; Lin and Matzarakis 2008; Shih et al. 2017) have observed strong influence of solar radiation on respondents' thermal perception and found respondents to be more sensible to variations in global solar radiation ($R^2 = 0.92$) than air movement ($R^2 = 0.79$). Similarly, Shih et al. (2017) found that occupants' thermal perception in spaces was more influenced by solar radiation than wind speed. Notable seasonal differences on the influence of solar radiation were observed by Lin (2009) who found that MRT strongly influenced the number of people visiting the square in the hot season. Conversely, in the cool season, the T_a was the determining factor on the use of the square. In addition, Lin et al. (2011) observed that in both the warm and cold seasons, as MRT increases, the percentage of those who "prefer stronger sunshine" decreases and the percentage who "prefer weaker sunshine" increases. The study concludes that operative temperature, which is the combination of MRT and T_a, strongly affects people's thermal perception.

Air temperature

The role of air temperature on the perception of thermal comfort in warm humid climates depends largely on the sub-climate in question. For the humid subtropical climates with pronounced winter and summer seasons, studies have shown more significant influence of T_a in winter than in summer (Lin

Table 3 Qualitative and quantitative results of studies on influence of urban fabric on outdoor thermal comfort in subclimates of warm humid tropical climates

	City, country	Source	Method	Thermal indices	Qualitative and quantitative results
A	Tropical savanna (Aw)				
1	Dar es Salaam, Tanzania;	Ndetto and Matzarakis (2013)	Simulation	PET	East–west-oriented streets were having worse pedestrian thermal comfort compared to north–south-oriented streets. Increase in building height to a maximum height of 100 m reduced both MRT and PET.
2	Dar es Salaam, Tanzania	Yahia et al. (2018)	Simulation	PET	Compact urban areas with high-rise buildings was having lower MRT and wind speed while vice versa was true for low-rise areas. Low-rise informal urban areas are more uncomfortable, and the shade seems an important factor than wind speed. Trees can reduce PET up to 14 °C.
3	Camagüey, Cuba	Rodríguez-Algeciras et al. (2016)	Simulation	PET	Aspect ratio between 1 and 1.5 provides acceptable thermal environment for summer and winter. Changing street orientation to N–S reduces heat stress in summer up to 2 h within the street. E–W street is uncomfortable throughout a day for H/W = 0.5. Similarity of PET is noticed between N–S and intermediate orientations, e.g., NE–SW and SE–NW.
4	Rajarhat Newtown, India	De and Mukherjee (2018)	Simulation	PET	Orientation angle of 30 and 60 with canyon H/W ratio of 2.5 has a potential to reduce the PET value by 5–9 °C during a mid-afternoon summer day.
B	Tropical rainforest (Af)				
1	Colombo, Sri-Lanka	Johansson and Emmanuel (2006)	Measurements	PET	Sites with high H/W ratio found to have lower temperature during the day and higher T_a during night. Differences of up to 20 K were observed for surface temperature between exposed and shaded areas.
2	Colombo, Sri-Lanka	Emmanuel and Johansson (2006)	Measurements	–	Urban–rural temperature differences were more significant and inter-urban differences reached 7 K. Maximum temperature decrease with H/W ratio was observed.
3	Colombo, Sri-Lanka	Emmanuel et al. (2007)	Simulation	PET	Vegetation had positive impact on reduction of PET. Also, PET decreases with an increase of H/W ratio to around 10 °C. Street orientation was found to have minor effect on PET.
4	Putrajaya, Malaysia	Qaid and Ossen (2015)	Measurement and simulations	–	An aspect ratio of 2–0.8 within asymmetrical canyons reduces the temperature of surfaces by 10 to 14 °C and T_a by 4.7 °C. Asymmetrical streets perform better than low symmetrical streets in facilitating wind flow and reducing MRT. The air temperature was reduced due to long hours of shading that reached up to 4 h from the northeast buildings.
C	Humid subtropical (Cfa and Cwa)				
1	Dhaka, Bangladesh	Kakon et al. (2009)	Measurement and simulations	THI	Street canyons with high SVF had higher solar radiation than those with low SVF. Deep canyons (low SVF) were 3.5–6 °C cooler than shallow canyons. THI was above the defined uncomfortable range.
2	Taichung, Taiwan	Lin et al. (2010)	Measurement and simulation	PET	In highly shaded areas, PET was < 22 °C while in barely shaded areas probability of PET < 22 °C was only 70%. Thermal comfort during summer was 50 and 20% in highly and barely shaded areas, respectively. High SVF leads to discomfort in summer and low SVF leads to discomfort in winter.
3	Dhaka, Bangladesh	Kakon et al. (2010)	Measurement and simulation	THI	Increase in building's height in a street canyon leads to lower SVF, less incoming solar radiation, lower mean radiant temperature and lower T_a.
4	Shanghai, China	Yang et al. (2011)	Measurement and simulation	PET	An increase of 0.4 in surface albedo lowered T_a at pedestrian level by 0.2–0.4 °C but increased MRT by 8–14 °C during the day. Increase of vegetation reduces MRT by 12–24 and 11–47 °C for grass and trees, respectively. PET can be reduced by 2–20 and 5–20 °C for grass and trees scenario, respectively.
5	Sao Paulo, Brazil	Johansson et al. (2013)	Simulation	TEP	MRT was higher in low-rise buildings compared to high-rise areas. Addition of vegetation reduces the surface temperature by up to 13 °C in low-rise areas. TEP can be reduced by 6 and 8 °C by adding vegetation in high- and low-rise areas, respectively.
6	Dhaka, Bangladesh	Sharmin et al. (2015)	Measurement and simulation	Ta	Deeper urban canyon was having 6.2 °C lower temperature than shallow canyons. Globe temperature, MRT and TOP showed positive and strong correlation with SVF and negative correlation with H/W ratio.
7	Tainan, Taiwan	Yang and Lin (2016)	Measurement and simulation	PET	Observed that aspect ratio of 3 can be considered as a threshold to outdoor thermal comfort. Also, planting trees is the most effective way of reducing the (PET)—by up to 15.2 °C. Improvement of design of outdoor spaces has a potential to reduce the frequency of heat stress from 79.7 to 40.5%.
8	Guangzhou, China	Zhang et al. (2017)	Simulation	SET	Street orientation has the largest contribution on SET at the pedestrian level of street canyons for a typical summer day. SE–NW-oriented street canyon provides better thermal comfort conditions than N–S or E–W-oriented. Contrary to previous studies, the N–S-oriented street canyons had a higher SET and worse comfort conditions in summer than the E–W-oriented street canyons due to wider spacing of the buildings for the N–S-oriented street canyon as per sunshine requirements. MRT and wind speed play key roles in pedestrian thermal comfort.
9	Hong Kong	Tan et al. (2017)	Measurement and simulation	PET	Influence of vegetation (road side trees) was noted in low-SVF (0.2) areas under cloudy conditions where PET was lowered to acceptable level of 29 °C from approximately 35–39 °C. Also, in exposed PET close to 46.3 °C was reduced to 37.6 °C beneath the tree canopy under cloudy conditions.

et al. 2011). According to Villadiego and Velay-Dabat (2014), people in the warm humid tropical savannah, which is dominated by small diurnal and yearly variations of air temperature, are highly sensitive to very small variations in air temperature. The study by Zeng and Dong (2015) in Chengdu, China, noticed strong connection between T_a and thermal perception votes of respondents who were located in shade; conversely, MRT and PET, which are significantly affected by solar radiation, were less important.

Air movement

Several studies (Ahmed 2003; Makaremi et al. 2012; Ng and Cheng 2012; Yin et al. 2012) investigated the influence of air movement on the thermal perception of respondents in warm humid tropical climates. Both Ahmed (2003) and Ng and Cheng (2012) found increased air movement to be an important factor in mitigating the heat stress in the urban area and the percentage of respondents that expressed neutral thermal perception increased gradually with increased air movement. The study suggests that lower temperature and higher wind speed can create a thermally neutral environment and alleviate the heat stress in summer. On similar grounds, Yin et al. (2012) found that the influence of wind on thermal perception was stronger in the shaded areas than in sunny areas, as shade tends to reduce the radiant heat gained by the human body as compared to a fully exposed location. Despite the fact that Makaremi et al. (2012) found significant differences regarding the wind perception of local and international students, both groups preferred an increase of the wind speed for reduction of thermal stress.

Influence of urban fabric on microclimate variations

Several studies (Emmanuel and Johansson 2006; Emmanuel et al. 2007; Johansson and Emmanuel 2006; Johansson et al. 2013, 2018; Kakon et al. 2009; Sharmin et al. 2015) have examined the influence of the urban fabric on the microclimate within urban canyons in different neighbourhoods in warm humid tropical climates. In the tropical rainforest climate of Colombo, Sri Lanka, Emmanuel and Johansson (2006) found that urban–rural temperature differences were more significant by day than by night. Both cool and heat islands were observed during daytime, and inter-urban differences reached 7 K, as most of the urban sites were cooler than the rural station. Furthermore, Johansson and Emmanuel (2006) showed that during a clear day, calculated PET values for all sites were generally above the assumed upper comfort limit of 33 °C during daytime, and, thus, thermal comfort was poor. On an overcast day, however, PET values varied less between sites both by day and by night and it did not go beyond assumed thermal comfort limits.

A difference in the morphological structure of urban areas presents different influences on microclimate, especially on shade and wind patterns. Compact urban forms with high buildings create deep street canyons with high H/W ratios. Such streets provide good shade (low MRT) whereas low-rise areas with low H/W ratios are exposed to the sun and result in high MRT (Emmanuel and Johansson 2006; Johansson and Emmanuel 2006; Emmanuel et al. 2007; Johansson et al. 2013; Yahia et al. 2018).

The prevailing wind direction and the surrounding buildings heavily influence wind patterns (Yang et al. 2011). In general, high H/W ratios lead to low wind speeds whereas low H/W ratio allows higher wind speeds (Yahia et al. 2018). Wide streets result in higher wind speeds (Emmanuel and Johansson 2006). Variations in building height play a role in creating higher turbulence around high-rise buildings, thus enhancing urban ventilation (Emmanuel et al. 2007; Sharmin et al. 2015). Parallel arrangement of buildings combined with setbacks to increase the distance between buildings (lowering the H/W ratio) facilitates and increases the wind speed (Emmanuel et al. 2007; Kakon et al. 2009). Moreover, asymmetrical aspect ratios may increase wind flow in urban canyons when tall buildings confront wind direction (Qaid and Ossen 2015).

Effect of aspect (H/W) ratio on outdoor thermal comfort

The aspect ratio is a physical factor of urban canyons, which affects the magnitude of urban heat islands and affects microclimatic and outdoor thermal comfort conditions (Qaid and Ossen 2015). Several studies (Ahmed 1994; Emmanuel and Johansson 2006; Emmanuel et al. 2007; Qaid and Ossen 2015; Rodríguez-Algeciras et al. 2016; Yang and Lin 2016; Zhang et al. 2017) investigated the influence of aspect ratio on the microclimate and consequently outdoor thermal comfort at pedestrian level in warm humid climates. Both Ahmed (1994) in Dhaka, Bangladesh, and Emmanuel et al. (2007) in Colombo, Sri Lanka, found that the enhancement of shade in the medium and high density urban settings showed a positive effect on the thermal comfort. Emmanuel et al. (2007) found that daytime PET values decrease with increasing H/W ratios; it leads to a decrease of around 10 °C PET for the high-density case. In Singapore, Yang and Lin (2016) observed that an aspect ratio of three could be considered as a threshold to achieve outdoor thermal comfort. In a study conducted in Dar es Salaam, Yahia et al. (2018) noticed that spaces between buildings in low-rise areas without vegetation are the most stressful spots (PET varies from 40 to 47 °C) when compared to those with less vegetation. Similar results were found by Johansson and Yahia (2012) who pointed out that the thermal conditions in Guayaquil, Ecuador, could be significantly improved (about 10 °C PET) by providing shading through trees or shading devices. Since high H/W ratios decrease the daytime temperature but increase the nocturnal air temperature, Johansson and Emmanuel (2006) pointed out that appropriate H/W ratios depend on the type of the neighbourhood, as a higher nocturnal temperature may be more acceptable in commercial areas than in residential ones. Several studies (De and Mukherjee 2018; Kakon et al. 2010; Zhang et al. 2017) have found that an increase in aspect ratio leads to a reduction of PET and consequently a decrease of thermal discomfort although it is difficult to bring it down within the comfort range at 2:00 pm.

The effect of SVF on outdoor thermal comfort

The sky view factor (SVF) is one of the commonly used urban fabric descriptors. It represents the ratio at a point in space between the visible sky and a hemisphere centred over the analysed location (Oke 1981). The SVF includes the buildings along the urban canyon and other objects, such as trees, and it can also be used in street intersections. As for other climates, studies (Chen and Ng 2012; Johansson et al. 2013; Kakon et al. 2009, 2010; Lin et al. 2010; Qaid and Ossen 2015; Rodríguez-Algeciras et al. 2016; Tan et al. 2017) in warm humid tropical climates have pointed out the influence of SVF on both microclimate and outdoor thermal comfort.

Studies (Kakon et al. 2009, 2010) found that thermal comfort (expressed as the temperature humidity index, THI) decreases with decreasing SVF. Similarly, Yahia et al. (2018) found a strong linear relationship ($R^2 = 0.97$) between the area-averaged SVF determined by ENVI-met and the average PET at 2 m. Similar relationship between SVF and T_a were found by Chen and Ng (2012) in humid subtropical Hong Kong and expresses the fact that the higher the SVF (the more open a site is to the sky) the more stressful is the thermal environment. In humid subtropical climates, with pronounced summer and winter seasons, it was observed that areas with low SVF result in improved comfort levels in summer but worsened thermal conditions in winter (Lin et al. 2010; Rodríguez-Algeciras et al. 2016).

Previous studies mentioned above linked SVF to people's perception of outdoor thermal environment; however, Krüger et al. (2011) noted that SVF, when analysed as an isolated parameter, is not able to accurately predict the thermal conditions of a particular site during daytime since incoming solar radiation has a stronger effect on MRT. For accurate results, the study suggests a combined analysis of the SVF and the solar trajectory and not SVF alone.

Effect of canyon axis orientation on outdoor thermal comfort

Canyon axis orientation is one of the important factors affecting the thermal environment of a street as observed in several studies in warm humid and other climates (De and Mukherjee 2018; Johansson 2006; Kakon et al. 2010; Ndetto and Matzarakis 2013; Rodríguez-Algeciras et al. 2016, 2017; Zhang et al. 2017). A simulation study by Johansson (2006) in Colombo, Sri Lanka, showed that for H/W ratios below 0.6, the influence of street orientation is marginal. However, for aspect ratios higher than that, north–south-oriented streets are more comfortable than east–west-oriented streets. The finding that north–south streets are more comfortable was confirmed by the study of Ndetto and Matzarakis (2013) in Dar es Salaam, Tanzania, and by Rodríguez-Algeciras et al. (2017) in Camagüey, Cuba. Johansson (2006) concluded that to achieve a noticeable improvement in outdoor thermal comfort in the climate of Colombo, east–west streets would need to be very deep, at least H/W = 4, whereas north–south-oriented streets would need to have an H/W ratio of at least 2. In Rajarhat Newtown, India, De and Mukherjee (2018) found that optimizing the orientation and canyon aspect ratio might reduce the thermal discomfort by a reduction of PET values of 5–10 °C during the most critical period of the day.

Challenges in the informal urban areas

The discussions in the previous sections focused on outdoor thermal comfort studies conducted in the formal urban fabric, which is the typical character of most of the developed world where most of the research has been carried out. Little is known on the subject of outdoor thermal comfort in informal settlements—also called slums, squatter settlements or shantytowns—and in this paper referred to as the informal urban fabric. These types of settlements mostly occur in developing and newly industrialized countries. According to Kombe (1995), too many, including bureaucrats and politicians see informal settlements as a transient phenomenon and an outcome of economic hardship which will ease once the national economy improves. However, this belief has proven to be a myth rather than reality. According to Hofmann et al. (2008), informal settlements are defined (1) as areas where groups of housing units have been constructed on land that the occupants have no legal claim to or occupy illegally and (2) as unplanned settlements and areas where housing is not in compliance with the current planning and building regulations (unauthorized housing). Studies by Huchzermeyer (2004) and Richards et al. (2006) have shown that in developing countries, informal urban areas are there to stay for the next decades and beyond.

In developing countries, urbanization is advancing in a very high speed, predominantly in the urban fringe (UN Habitat 2016). This rapid urbanization is directly linked to the growth of informal settlements in Latin America, East Asia and Sub-Saharan Africa. According to Augustijn-Beckers et al. (2011), important reasons for informal settlement growth are the weakness of statutory planning and the strong rural–urban migration. The latter, in combination with natural population growth, is leading to substantial urban population growth.

Challenges of informal neighbourhoods span from social, economic and environmental; however, the discussion in this paper focuses on decreased outdoor thermal comfort. It is an established fact that areas with poor urban design will experience decreased thermal comfort in hot/warm climates which has a negative effect on people's well-being and may have serious consequences for health (Johansson 2006). Improvement of the outdoor environment in the informal urban fabric in terms of microclimate and outdoor thermal comfort will not only create a better outdoor environment but also improve the indoor environment.

Outdoor thermal comfort in informal urban fabric

Only a few studies (Kakon et al. 2009; Yahia et al. 2018; Sharmin et al. 2015) have compared the outdoor microclimate and the thermal environment between the informal urban fabric and the formal urban fabric in warm humid climates. In Dhaka, Bangladesh, Kakon et al. (2009) compared the informal urban area of Siddeswari (H/W = 1.88) with the formal areas of Motijheel and Dhanmondi with H/W ratios of 0.47 and 0.92, respectively. The researcher found that THI reached up to 35.3 °C in Dhanmondi, 34.7 °C in Siddeswari and 34.5 °C in Motijheel, thus being higher (> 26 °C) than acceptable comfort limits in all canyons. In terms of thermal comfort, it was noted that Dhanmondi is the most uncomfortable (hottest) and Motijheel is more uncomfortable than Siddeswari due to the fact that in Siddeswari the duration of strong solar radiations is short and it has the lowest SVF. In comparison, in another simulation study in Dar es Salaam, Tanzania, Yahia et al. (2018) compared maximum PET of the informal urban area of Manzese (mostly single-story compact dwellings) with three formal urban areas, Upanga (mainly medium-rise, green area), Kariakoo (very dense area with 2–10-story buildings) and the city centre (medium- to high-rise buildings). The study found that informal Manzese was the most uncomfortable area with PET values above the comfort range for Dar es Salaam of 23–31 °C (Ndetto and Matzarakis 2016). Sharmin et al. (2015) compared a traditional area (informal with H/W = 1–4) with planned areas (H/W = 1.2–2.75). In this study, it was found that the informal urban areas, which have variable urban forms with irregular plot sizes and building heights, responded positively to the synoptic climate, while the planned areas, with uniform plot sizes and height, showed a tendency to develop a daytime urban heat island effect. Despite the fact that the morphological structure of the informal urban fabric in these studies differs, it could be concluded from the studies that low-rise compact informal urban fabrics morphologically presents a challenging outdoor thermal environment.

Apart from the calculated thermal comfort in the above-mentioned studies in informal settlements, little is known on the subjective thermal perception of urban dwellers residing in these settlements. Most of the studies on outdoor thermal comfort have dealt with either recreational spaces (such as parks, squares and open spaces) or transient spaces (such as train stations, bus terminals, semi-outdoor spaces and streets). Only a few studies (Li et al. 2016a) have investigated the outdoor thermal environment in the areas where people live. Knowledge of people's thermal perception of outdoor thermal comfort in informal settlements is important as these areas are places for living and working. A review of different approaches for the informal urban fabric upgrading has been discussed by Abbott (2002); however, none of the approaches have taken into consideration integrated issues of microclimate and thermal comfort of the urban dwellers who live in these areas.

Conclusion

The objective of this paper was to review studies on outdoor thermal comfort in warm humid climates and to highlight challenges brought up by rapid urbanization in terms of thermal comfort in the informal urban fabric. A number of studies presented in this review have shown the development and growing interest of research on outdoor thermal comfort in warm humid climates in the past decade. Although results vary between studies, it can be concluded that the levels of neutral temperature and thermal comfort ranges are higher in warm humid climates than in colder climates. There is also a difference between tropical rainforest (Af) and tropical savannah (Aw) on one hand and humid subtropical (Cfa) on the other. The latter, which is characterised by pronounced summer and winter seasons, has a larger difference between seasons as regards the neutral temperature and the comfort range than the former two, which are characterised by small annual differences. Despite the dweller's higher tolerance to heat, it is difficult to achieve thermally comfortable conditions during the hottest part of the day in the tropical rainforest and tropical savannah climates, as well as during the warm season of the humid subtropical climates. Shade through buildings (high H/W ratio) and/or shading devices or vegetation is necessary to reduce heat stress. In addition, ventilation should be enhanced.

Most of the studies in this review have focused on transient spaces (e.g. bus and train stations) and recreational areas (e.g. parks and squares) of the formal urban fabric, which represents a small portion of the cities. In developing countries, the mentioned areas of the planned formal sector might not represent as much of the city structure as the informal urban fabric does. This review found that only few studies (Kakon et al. 2009; Sharmin et al. 2015; Yahia et al. 2018) compared formal and informal urban fabric in terms of outdoor thermal comfort. Moreover, none of the mentioned studies has investigated people's perception of outdoor thermal comfort in the informal urban fabric. Further studies to unveil the urban dwellers' perception of outdoor thermal comfort in informal urban fabric of warm humid climates as well as coping strategies, thermal neutrality, thermal preference and comfort limits are necessary. Addressing these areas will not only further our knowledge of thermal comfort but also bring forward key items of policy implications on the upgrading of informal settlements.

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Paper II

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Urbanites' thermal perception in informal settlements of warm-humid Dar es Salaam, Tanzania

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1. Introduction

Outdoor microclimate of an urban area can significantly influence thermal comfort of the urbanites residing in it. In the context of warm humid climates where periods of high thermal stress dominate throughout the year, urbanites spend most of their time outdoors. In such an environment, the need to improve outdoor thermal conditions is a necessity for enjoyment of public spaces (Lin, 2009) and improvement of the quality of urban living (Chen and Ng, 2012).

The rapid growth of informal settlements in most of the cities in developing countries has left the cities with a weak position to handle associated social and environmental problems in a sustainable way (Roth, 2007). This growth poses climate–related environmental problems, which are linked to the deterioration of the outdoor thermal environment such as poor dispersion of air pollutants (generally low wind speeds and lack of ventilation) and high level of heat stress which decreases productivity, reduces human comfort and increases mortality due to heat related illness (Johansson, 2006; Roth, 2007). Furthermore, most of the cities in developing (sub) tropical countries lack adequate financial, technological, and scientific means to effectively research and mitigate these problems. These countries deal with other more pressing issues of daily survival that are more important (Roth, 2007).The assumptions that findings of studies on thermal perception of the thermal environment in a planned context can be applicable to informal urban fabric can lead to a lack of interest to investigate thermal perception of the latter (Baruti et al., 2019). Therefore, the possibility of improving thermal environment in these areas will be lessened.

On the other hand, the necessity to improve the outdoor thermal environment in warm humid climates has resulted into a number of studies over the last decade. Several studies on outdoor thermal comfort and thermal perception of urbanites in warm humid tropical climates have been conducted, for example, (Spagnolo and de Dear, 2003; Hwang and Lin, 2007; Lin and Matzarakis, 2008; Lin, 2009; Makaremi et al., 2012; Ndetto and Matzarakis, 2016; Johansson et al., 2018) to mention a few. However, the challenge is that most of these studies have addressed the formal urban fabric context and hence little is known on the thermal perception of outdoor thermal environment for the urbanites residing in informal settlements, which typically accommodates 30–85% of the population of cities in developing countries (Kombe, 2005).

Knowledge of urbanites' thermal perception of the thermal environment in the context of informal settlements is of paramount importance not only due to the huge population residing in it but also due to the need to ensure a sustainable environmental development. The Millennium Development Goals (MDGs) (United-Nations, 2009) emphasize the need to “ensure environmental sustainability” and to achieve “a significant improvement in the lives of at least 100 million slum dwellers worldwide.” The gravity of the challenges brought about by the thermal environment can better be illustrated by an analytical study focused on the informal urban fabric where these urbanites experience their daily lives and not only in the public areas where they go for leisure and enjoyment.

Focusing on Dar es Salaam, which has a warm humid tropical climate (Aw according to the Köppen classification), this study

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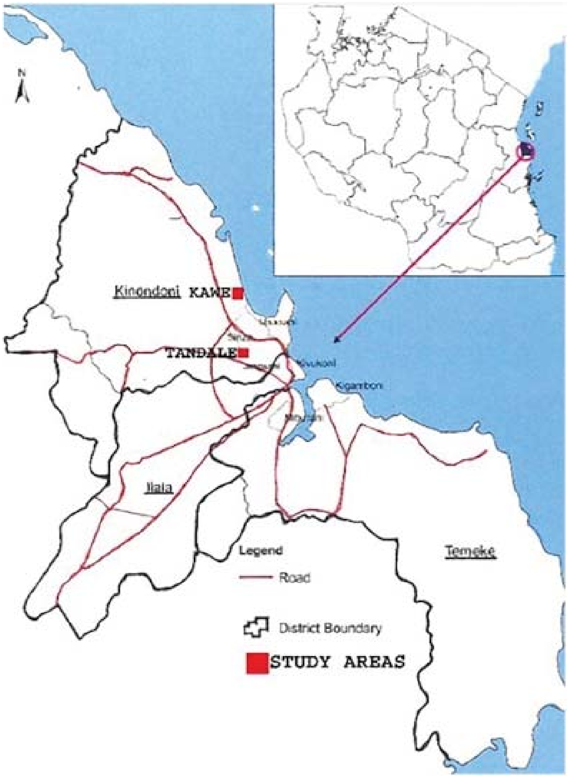

Fig. 1. Geographical location of Dar es Salaam in Tanzania (top-right corner) and study areas locations within Dar es Salaam. Edited from (Mboera et al., 2016).

investigates the following: first, the urbanites thermal perception of the outdoor thermal environment in the informal settlements and second, the extent of application of different behavioural adaptation measures by urbanites. Previous studies in the formal urban fabric of warm humid climates have shown that comfortable ranges varies within sub-climates. For example, within the tropical savannah, it ranges between 24 and 30 °C (Yang et al., 2013b) and 22–30 °C (Trindade da Silva and Engel de Alvarez, 2015). Additionally, in the humid sub-tropical, it ranges between 15 and 22 °C (Liu et al., 2016) and 19–30 °C (Cheng et al., 2012). To the authors' knowledge, there is no study, which is carried out in informal settlements to examine the thermal comfort. Contrary to the majority of previous studies that have been conducted in public places where people go for leisure, this study has been conducted in the middle of two neighbourhoods where 64% of the interviewees live and 28.1% work and experience their daily lives.

2. Methods

2.1. The City of Dar es Salaam

Dar es Salaam is located along the coastal belt of the Indian Ocean (Fig. 1) at latitude 6° 53′S and longitude 39° 17′E. The city covers an extensive area of 35 km north to south, and up to 30 km from east to west (Briggs and Mwamfupe, 2000). According to the general census report of 2012, Dar es Salaam had a population of 4.36 million accounting for 10% of the total Tanzania Mainland population with an average annual growth rate of 5.6% in the years 2002–2012 (National-Bureau-of-Statistics, 2013).

In terms of urbanization, the city is dominated by an unprecedented growth of informal settlements, which constitutes the major and most vibrant sector shaping urban growth (Kombe, 2005). Informal settlements hereby referred to as the informal urban fabric

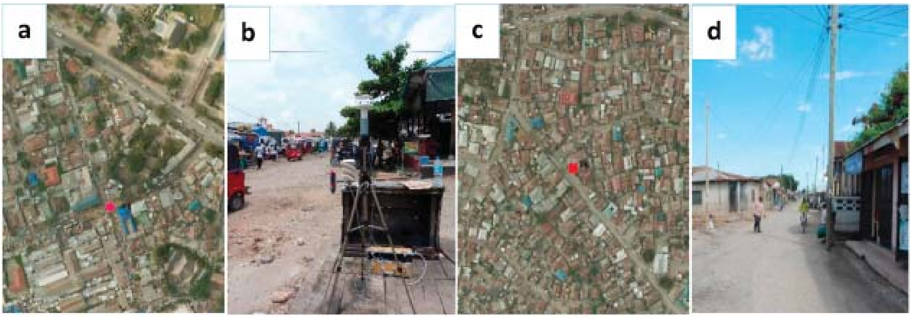

Fig. 2. Study areas within Dar es Salaam (a&b)-Kawe markert and (c&d)-Tandale Ali Maua Street. The red dot indicates areas where micrometeorological measurements were carried out. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

are urban areas that develop and grow without planning, and in which basic facilities are mostly lacking. The term 'informal' refers to the settlements that are usually built without legal tenure and do not follow established building and planning regulations (Abbott, 2003). Abbot (2003) pointed out that the major reasons for informal settlement growth are the weaknesses of statutory planning and a strong rural–urban migration, leading to substantial urban population growth.

2.2. Study areas

Two informal urban settlements, Kawe (6°44′S, 39°13′E) located close to the coast of the Indian Ocean and Tandale (6°47′S, 39°14′E) located inland, were selected for this study. The mentioned neighbourhoods typically represent examples of informal settlements categorised in the urban type known as consolidated high density, low-rise informal settlements (Lupala, 2002). The typical character of these neighbourhoods is narrow and winding streets due to compactness of the building structures. In addition, streets are dominated by informal sector activities.

2.2.1. Kawe

Kawe ward has a population of 67,115 with an average household size of 4.0 (National-Bureau-of-Statistics, 2013). A busy street, Kawe Sokoni (local neighbourhood market) was selected for both the survey and the micrometeorological measurements. Fig. 2(a&b) shows part of the neighbourhood with the location where the survey (red dot) was conducted (a) and a street view (b). The street is located 1.5 km from the coast of the Indian Ocean and 11.8 km from the city's central business district (CBD). The street is vibrant with small-scale businesses, that is, shops, vendors, motorbike taxies (bodaboda), local restaurants, bars, and food market. The majority of the respondents were involved in small-scale businesses either buying or selling; or they were passers-by heading to/from home.

2.2.2. Tandale

Tandale ward has a population of 54,781 with an average household size of 3.6 (National-Bureau-of-Statistics, 2013). A Street named Ali-Maua was selected for the survey and the micrometeorological measurements. The Street is located 7.2 km from the city's central business district and 5 km from the coast of the Indian Ocean. Fig. 2(c, d) shows part of the neighbourhood with the location where the survey (red dots) was conducted (c) and a street view (d). The street is active with small-scale informal businesses involving vendors, small shops and others selling local foods. The majority of the respondents were either residents of the area or working in the neighbourhood in different formal and informal businesses.

2.3. The climate of Dar es Salaam

Dar es Salaam has a warm humid climate, with the annual mean maximum temperature varying between 29 °C and 32 °C, while the annual mean minimum temperatures vary between 19 °C and 25 °C (Fig. 3a). The highest temperatures are experienced in December–March, while the cool period with relief in thermal stress is between May and September. Relative humidity remains high throughout the year; it is about 75% most of the time, but it may vary from 55% during daytime to almost 100% at night. According to the Köppen classification (Kottek et al., 2006), the climate is categorised as warm humid tropical savannah (Aw). Dar es Salaam has two distinct seasons mostly influenced by the inter-tropical convergence zone (ITCZ); the northeast monsoon between March and October, and the southeast monsoon between October and March (Jonsson et al., 2004). High solar radiation and wind speed dominates the months of October to February (Fig. 3b). In this study, the months of March and July were selected to represent warm and cool seasons respectively.

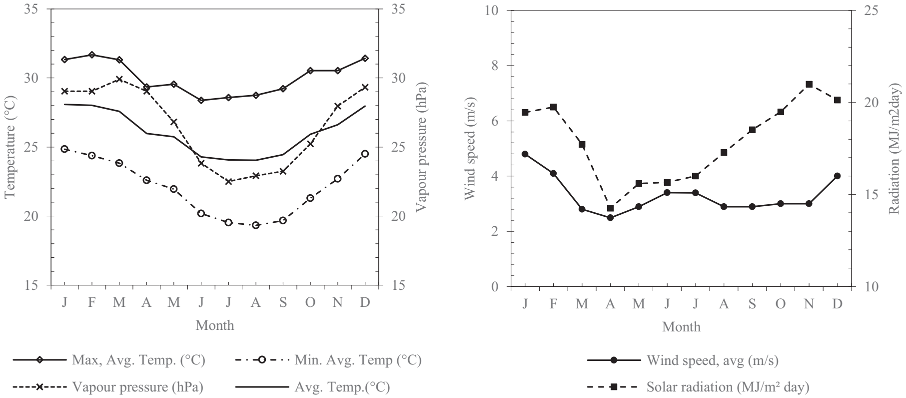

Fig. 3. The climate of Dar es Salaam, Tanzania. (Left) Average maximum and minimum temperature and vapour pressure, (right) mean daily wind speed global solar radiation (Source: Meteonorm v.7 (Meteotest, 2014).

2.4. Respondents

The total number of respondents who participated in the field campaign was 1541 of which 746 in the warm season and 795 in the cool season. The numbers of respondents from Kawe were 779 while in Tandale were 764. As shown in the characteristics of respondents presented in Table 1, there was equal participation of male and female. Young (52.7%) and middle aged (24.3%) were the majority of the respondents and almost half of them (46.4%) had already spent > 3 h outdoors at the time of the interview.

One of the notable observations is that the percentage of male respondents was higher (55.3%) in the warm season while in the cool season, the percentage of female respondents was higher (54%) compared to their male counterpart.

2.5. Meteorological measurements

A mobile meteorological station was used to measure the micrometeorological variables, that is, air temperature (T_a), globe temperature (T_g), relative humidity (RH), wind speed (ν) and wind direction. A data logger (Campbell CR800) was used to connect the sensors in which 1-min averages were sampled. The measurement height was 1.1 m, corresponding to the average height of the centre of gravity for an adult (Mayer and Höppe, 1987). Wind speed was measured at 1.5 m height by the use of a two-dimensional ultrasonic sensor (Gill windsonic) which detects speeds down to 0.02 m/s. Gill windsonic measures the horizontal component of the wind speed only. Since the urban wind pattern is often irregular and includes vertical movements, there is a possibility that the wind speed was slightly underestimated. The wind speed at 1.1 m was determined as shown in Eq. 1 (Aynsley et al., 1977):

Table 1
Respondents' characteristics.

Some characteristics of respondents (%); N = 1541			
Sex	Male	780	50.6%
	Female	761	49.4%
Age group	Less or equal to 20	150	9.8%
	21–35	826	53.7%
	36–50	374	24.3%
	51–65	135	8.8%
	66–80	52	3.4%
	> 80	1	0.1%
Time spent outdoor	Less than one hour	216	14.0%
	Between 1 and 2 h	304	19.8%
	Between 2 and 3 h	304	19.8%
	> 3 h	714	46.4%
Activity	Sitting	524	34.0%
	Standing	316	20.5%
	Walking	703	45.6%

$$\nu_{1.1} = \nu_{1.5} \times \left(\frac{1.1m}{1.5m}\right)^{\alpha} \quad (1)$$

where $\nu_{1.1}$ is the wind speed at 1.1 m, $\nu_{1.5}$ is the wind speed at 1.5 m and α is the mean speed exponent which depends on the roughness of the ground (e.g. α = 0.25 for parks and suburbs and α = 0.36 in the centre of large cities (Aynsley et al., 1977). The formula is valid for an open terrain and it might be less accurate in the urban context. However, since the difference in wind speed at 1.1 m and 1.5 m is small, the wind speed is assumed to be accurate.

The meteorological station was placed at open locations so that the station would be in the sun during the whole period of measurements. The sensor for air temperature and humidity (Rotronic Hydroclip S3) has a long response time and therefore a 5-min interval was allowed prior to the beginning of the measurements. A white, naturally ventilated radiation shield as shown in Fig. 2b covered the sensor.

In parallel to the micrometeorological measurements at the sites, there was a fixed meteorological station mounted at the roof of the House of Culture (National Museum) in the city centre. This station measured T_a, RH, wind (speed and direction) and global solar radiation (GR). A data logger (Campbell CR1000) was used to connect the sensors to which 10-min averages were sampled. The measurement height for T_a, RH and GR was 10 m above street level whereas wind speed and direction was measured at 3 m above roof level (thus 13 m above street level). The probe for the T_a and RH measurements (which was the same as for the micrometeorological measurements) was kept inside a white aspirated radiation shield (Young 43,502). GR was measured by a Kipp & Zonen CMP 11 pyranometer whereas the wind was measured with the same instrument as for the micrometeorological measurements.

2.6. Calculation of the mean radiant temperature

The mean radiant temperature (T_{mrt}), was calculated from measured values of globe temperature (T_g), T_a and ν. Calculation of T_{mrt} considers both short and long wave radiation and represents the weighted mean temperature of an imaginary enclosure that gives the same radiation as the complex urban environment (ISO-7726, 1998). The globe thermometer is equipped with a quick responding pt100 sensor inside a plastic (celluloid) table tennis ball painted flat grey (colour RAL 7001) according to (Thorsson et al., 2007). It has a diameter, D, of 40 mm, weigh 3 g, and its emissivity, ε, was assumed to be 0.97. Thorsson et al. (2007) calibrated the thermometer in a study in Göterborg, Sweden, with measurements of short wave and longwave radiation in six directions (downward, upward, north, south, east, and west) which resulted in the following formula for determining T_{mrt}:

$$T_{mrt} = \left[(T_g + 273)^4 + \frac{1.335 \times 10^8 {v_a}^{0.71}}{\varepsilon D^{0.4}} \times (T_g - T_a)\right]^{0.25} - 273.15 \quad (2)$$

where T_g = globe temperature (°C), ν_a = wind speed (m/s), T_a = air temperature (°C), D = globe diameter (mm) and ε = globe emissivity.

The globe thermometer has a time constant of about 5 min (Nikolopoulou et al., 1999) which is much shorter than that of the standard indoor 150 mm copper globe thermometer having a time constant of 20–30 min (ISO-7726, 1998). T_{mrt} calculated in this way is very sensitive to variations in the wind speed. For example, an increase in wind speed will make a globe cool down and T_g decrease and result in overestimated T_{mrt} (Johansson et al., 2014; Johansson et al., 2018). In order to reduce sensitivity to variations of wind speed, 10 min averages of wind speed and 5 min averages of air and globe temperature were used in the calculations of the T_{mrt}.

2.7. Thermal comfort investigation

2.7.1. Thermal index used

In this study, the thermal environment was investigated using the Physiological Equivalent Temperature (PET). PET is based on the Munich energy balance model for individuals (MEMI) and it is defined as the air temperature at which the energy balance for the assumed indoor condition is balanced with the same mean skin temperature and sweat rate as calculated for the actual outdoor condition (Mayer and Höppe, 1987). The PET index was developed by considering the effects of short and long wave radiation fluxes in the outdoor environment based on the human energy balance and it is the most used thermal index today and has been found to work well in tropical climates (Johansson, 2016; Potchter et al., 2018).

2.7.2. Thermal comfort zones

In this study, the comfort limits for 20% unacceptability were calculated. Comfortable votes were considered those falling into central categories (−1, slightly cool; 0, neutral; 1, slightly warm) of the thermal sensation scale (Spagnolo and de Dear, 2003; Lin, 2009).

2.7.3. Neutral PET index value

Bins for the PET index were created at an interval of 1 °C. The neutral value was determined by firstly grouping all thermal sensation votes < 0, cooler than neutral and votes > 0, warmer than neutral. Secondly, votes, which were equal to 0, were randomly and equally divided between two groups. By using Probit analysis (Ballantyne et al., 1977), the neutral PET index was determined as the value at which 50% of the sample voted cooler than neutral and 50% voted warmer than neutral. Statistical package for social sciences (SPSS) was used to perform the Probit analysis.

2.7.4. Preferred PET index value

In this study, the preferred PET index value was determined as the value at which 50% of the respondents prefer the temperature to be cooler and 50% prefer it to be warmer. It was determined following the same procedure as for the neutral PET index value above.

2.8. Structured interviews

Structured interviews were conducted in both Kawe and Tandale. Respondents were asked questions by interviewers who filled out the questionnaire for estimation of their subjective thermal sensation. All respondents were volunteers. The questionnaires were translated into the Swahili language, the English version is attached as Appendix 1. The ASHRAE 7-point scale for thermal sensation votes was used (see Appendix 1). The decision to use the seven-point scale is based on the results of a piloting fieldwork that showed that the majority of the respondents were within the 7-point scale. In addition, diurnal variations of microclimate in the warm humid tropical savannah are small compared to climates with pronounced summer and winter seasons. A seven-point scale has also been used in many other studies such as (Spagnolo and de Dear, 2003; Hwang and Lin, 2007; Ndetto and Matzarakis, 2016).

Respondents were also requested to report their thermal sensation and preference in relation to variables of atmospheric weather conditions, which are air temperature, wind speed, solar radiation and humidity on a 3-point scale (McIntyre, 1980), see Appendix 1. Moreover, the survey questionnaire comprised of questions about gender, age, time spent outdoors, activity, reason for being in the place as well as coping strategies during extreme weather conditions. The type of clothing and activity were observed by the interviewer and chosen from a predefined list. Activities before the interview were defined as sitting, walking, and standing; however, during the interview, respondents were normally standing.

3. Results

3.1. Micrometeorological measurements

Table 2 presents measurements conducted in different seasons for both informal settlements (Kawe and Tandale) of Dar es Salaam. In both settlements, air temperature (T_a), globe temperature (T_g), wind speed (ν) and direction, relative humidity (RH) were measured directly from the field while the mean radiant temperature (T_{mrt}) was calculated from measured values of globe temperature (T_g), T_a and ν. The average wind speeds during the survey were observed to be 1 m/s and 1.3 m/s in warm and cool seasons respectively.

As predicted, informal urban fabric areas have shown significant low wind speeds during the measurement periods in both seasons. Air temperatures are stable between 29 and 33 °C in both seasons. There were no significant differences between the warm and cool seasons in terms of air temperatures during the measurement periods. However, there are notable differences in vapour pressure between the seasons (Table 2).

Table 3 presents results from the city centre's meteorological station for T_a, vapour pressure, and wind speed. T_a shows only slight differences between the two seasons. However, there was a significant difference in the vapour pressure about 10 hPa higher values in the warm season. Average wind speeds were higher in the formal urban fabric areas especially in the cool season. It is worth mentioning that the meteorological measurements in the city centre were taken at 3 m above the canopy layer, wind speeds were converted to 1.1 m by the formula provided in section 2.5 in Eq. 1.

Table 2
Measurement data for each field campaign including season, date, site, time, number of interviews as well as average wind speed, vapour pressure, air, globe and mean radiant temperatures for different measurement periods.

Season	Date	Site name	Measurement period	No. of interviews	ν_{avg} (m/s)	VP_{avg} (hPa)	$T_{a,avg}$ (°C)	$T_{g,avg}$ (°C)	T_{mrt}(°C)
Warm/Rainy	16-03-2017	Kawe	11:46–16:31	231	0.7	32.2	32.3	36.9	51.8
	17-03-2017	Kawe	10:53–13:08	151	1.0	31.3	32.9	40.7	68.1
	18-03-2017	Tandale	12:40–15:10	164	1.1	27.7	32.8	37.8	57.4
	20-03-2017	Tandale	11:36–18:06	202	1.5	31.2	32.1	35.3	50.1
Cool/Dry	25-07-2017	Kawe	12:26–16:26	200	1.6	21.6	31.1	34.9	55.7
	26-07-2017	Kawe	11:46–16:46	199	0.7	21.6	30.3	34.4	46.6
	27-07-2017	Tandale	13:46–17:14	200	1.1	21.8	29.1	29.8	33.8
	28-07-2017	Tandale	12:53–17:23	196	1.8	18.1	30.9	33.9	51.3

Air temperature (T_a, °C), wind speed (v,m/s), globe temperature (T_g, °C), mean radiant temperature (T_{mrt} °C). The vapour pressure (VP) was calculated based on T_a and relative humidity.

Table 3
Measurements from the meteorological station in the city centre (House of Culture). The average T_a, VP and wind speed are both full day and measurements hours at Kawe and Tandale. The area is planned and measurements were taken in the top of the roof above street canopy layer.

Season	Date	Measurements average during field campaign				Full day average measurements			
		Measurement period	v^{a}_{avg} (m/s)	VP_{avg} (hPa)	$T_{a,avg}$ (°C)	Measurement period	v_{avg} (m/s)	VP_{avg} (hPa)	$T_{a,avg}$ (°C)
Warm	16-03-2017	11:46–16:31	1.8	32.3	32.0	00:00–23:50	1.0	31.5	29.8
	17-03-2017	10:53–13:08	1.6	32.7	33.2	00:00–23:50	1.1	30.3	29.5
	18-03-2017	12:40–15:10	1.9	31.3	33.5	00:00–23:50	1.1	30.2	30.0
	20-03-2017	11:36–18:06	2.2	32.9	34.5	00:00–23:50	1.3	32.0	30.0
Cool	25-07-2017	12:26–16:26	2.0	22.7	31.0	00:00–23:50	1.4	24.0	26.6
	26-07-2017	11:46–16:46	2.5	22.6	29.3	00:00–23:50	1.6	23.9	26.0
	27-07-2017	13:46–17:14	2.1	22.3	28.8	00:00–23:50	1.2	22.7	25.6
	28-07-2017	12:53–17:23	2.3	19.3	30.6	00:00–23:50	1.4	21.6	26.1

[a] Wind speed was converted from 13 m height to 7 m for comparison purposes. Surface roughness coefficient was estimated to be 0.28.

3.2. Subjective thermal comfort

3.2.1. Thermal sensation

Fig. 4 shows the percentage distribution of thermal sensation votes (TSV) in the cool and warm seasons for Kawe and Tandale areas. Interestingly, in the warm season, the TSV's show no significant differences between the two places despite the fact that measurements were taken in different days. As expected in the warm season, the distribution of votes on the ASHRAE scale in Fig. 4 is skewed towards the 'warm' end of the scale for both areas. In the cool season, there was a statistically significant difference in the respondents' TSV between Kawe (M = 4, SD = 0.72) and Tandale (M = 3.8, SD = 1.0) conditions; t (4.4), p = .00. Majority of respondents (62%) in Kawe voted neutral (TSV = 0), whereas in Tandale, it was only 35%. In general, the TSV's in the cool season showed that > 90% of respondents voted within the three central categories ("slightly cool," "neutral", "slightly warm"), whilst the percentage of respondents who felt cold or hot were below 2%.

3.2.2. Thermal acceptable range

Fig. 5 shows the relationship between thermal sensation votes and PET for the warm, cool, and combined seasons. In the warm season, as the PET index temperature increases, the mean thermal sensation vote (MTSV) of the respondents' inclines towards the hot side. The relationships between MTSV and PET in the warm and combined seasons are not linear. They can be explained by polynomial functions in the warm (R^2 = 0.8) (Fig. 5a) and in the combined season (R^2 = 0.88) (Fig. 5b) respectively. In the cool season, the relationship is explained by a linear function (R^2 = 0.79) (Fig. 5a).

A simple regression analysis of the relationship for the warm, cool, and combined seasons for Dar es Salaam's informal settlements resulted in the following equations:

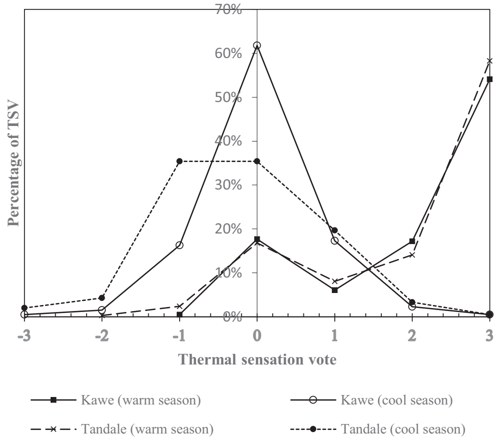

Fig. 4. Distribution of TSV in the cool and warm seasons for both Kawe and Tandale settlements.

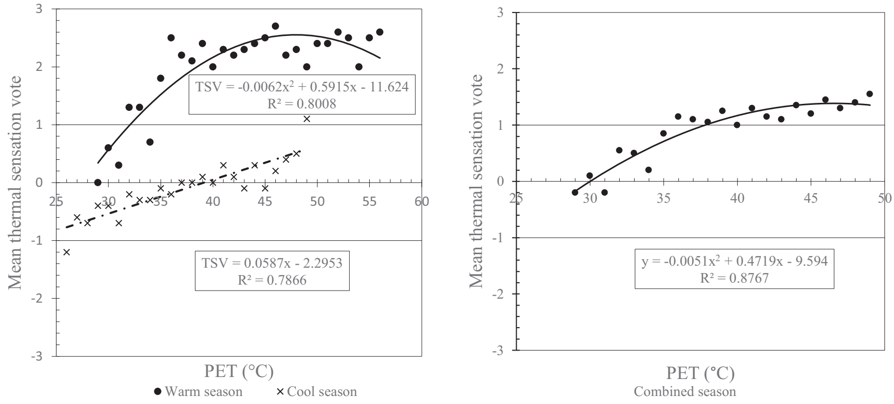

Fig. 5. The relationship of thermal sensation votes and PET for (a) the cool season (n = 795) and warm season (n = 746) and (b) combined seasons based on 1 °C average bin.

a) For warm season

$$MTSV = -0.006PET^2 + 0.591PET - 11.62 \ (R^2 = 0.8) \quad (3)$$

b) For cool season

$$MTSV = 0.0587PET - 2.295 \ (R^2 = 0.78) \quad (4)$$

c) For combined seasons

$$MTSV = -0.0051PET^2 + 0.472PET^2 - 9.594PET \ (R^2 = 0.88) \quad (5)$$

It is worth noting that the warm and combined seasons are more representative of the thermal conditions in this climate as the cool season is short (June–September); hence, thermal acceptable ranges for warm and combined seasons were determined by considering MTSV between −0.5 and 0.5. Based on the above Eqs. (3)–(5) and Fig. 5(a&b), the thermal acceptable range is 25.8–29.8 °C PET and 27.6–32.1 °C PET for the warm and combined seasons respectively. Although it does not seem practical in terms of application, the thermal acceptable range for the cool season based on Eq. 4 is 30.6–47.6 °C PET. It is worth to point out that the cool season presents a drastic decrease in vapour pressure and a slight decrease in T_a (Fig. 11&12). Such changes could have contributed to the way the urbanites responded in the cool season as further described in the discussion section.

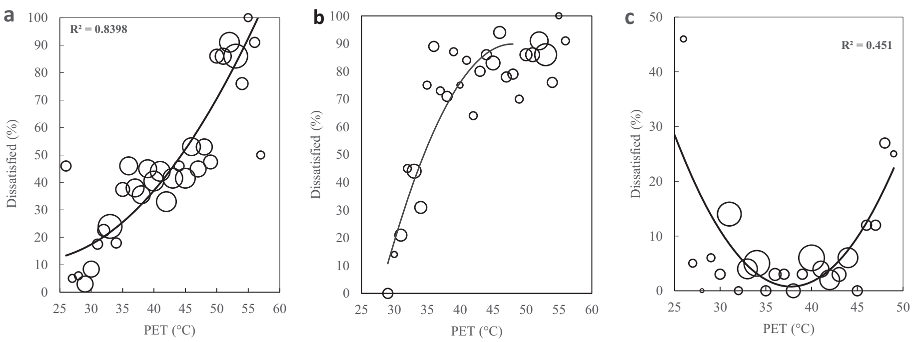

Fig. 6. The relationship between percentage of dissatisfied and PET for (a) combined warm and cool season, (b) warm season, and (c) cool season. The size of markers is proportional to the number of votes in each bin.

Table 4
Neutral and preferred PET index values and upper comfort limits (20% unacceptability values) for the warm, cool and combined seasons.

	Neutral PET index value by Probit technique		Neutral PET index value by bins (Fig. 5)	Preferred PET index value by Probit technique (Fig. 7)		Thermal acceptable ranges by bins (Fig. 5)	Upper comfort limits (Fig. 6)
Seasons	$T_{neut.}$ (°C)	Chi-square test of independence	$T_{neut.}$ (°C)	$T_{pref.}$ (°C)	Chi-square test of independence	(°C)	(°C)
Combined	33.5	X^2 (19) = 22.3; p = .270	30.2	21.5	X^2 (19) = 20.7; p = .353	27.4–33.6	31.8
Warm	27.5	X^2 (27) = 74.3; p < .001	27.7			25.8–29.8	30.2
Cool	39.5	X^2 (23) = 14.5; p = .912	39.1	25.5	X^2 (23) = 18.7; p = .718	30.6–47.6	48.2

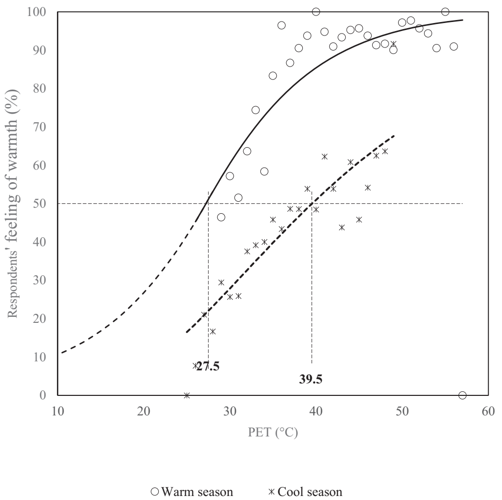

Fig. 7. The relationship of respondents' feeling of warmth and PET in the warm and cool seasons by the Probit analysis.

It is suggested that the central three categories of the TSV scale defines respondents who are comfortable (de Dear and Fountain, 1994; Lin, 2009). Fig. 6 shows the relationship between respondents' percentage of dissatisfied and PET for the combined warm and cool seasons (a), warm season (b) and cool season (c). Fig. 6(a & b) shows that at an intersection of fitted curves at the 80% acceptability limit (20% unacceptability), the value for PET is 31.8 °C and 30.2 °C (see Table 3) which marks the upper boundaries of thermal comfort range for the combined and warm seasons respectively. The cool season (Fig. 6c) shows how the cool season gives relief to the respondents; however, the thermal comfort zone is too large for practical application.

3.2.3. Neutral PET index temperature

The neutral PET index temperature is the temperature at which people feel thermally neutral implying that they neither feel cool nor warm (Lin, 2009). In this study, the neutral index temperature in the warm, cool, and combined seasons using both the linear regression and the Probit technique (Ballantyne et al., 1977) was determined and a summary of the results is presented in Table 4. Fig. 7 marks the neutral PET index temperatures for the warm season (27.5 °C PET) and for the cool season (39.5 °C PET). The study noticed minor differences (ranging from 0.2–0.4 °C) between neutral index temperatures determined by regression and the Probit technique for the warm and cool seasons with exception of the combined season. In addition, disparity between the proportions of respondents who feel neutral in the warm season as compared to cool season is vividly noticed.

3.2.4. Preferred PET index temperature

Analysis of the respondents' preferred PET index temperature was also conducted using the Probit technique. As pointed out by Lin, (2009), preferred PET index temperature is the temperature people want. Fig. 8 shows preferred PET index temperature for the cool season and combined seasons, which is 25.5 °C and 21.5 °C PET respectively. The summary of results is as presented in Table 4. For the warm season, it was not possible to determine the preferred PET index temperature.

3.3. Preference for microclimate variables

The respondents' preference for microclimate variables that influences thermal comfort was assessed and compared for both warm and cool seasons. These variables were limited to Ta, sun, wind and humidity as shown in Fig. 9. Results (Fig. 9a) show a high desire for cooler environment among respondents in both the warm season (83%) and the cool season (59%); only 3.6% of the respondents desire it to be warmer in both seasons. The respondents' desire for more wind is high in both the warm (74.3%) and cool (58.4%) seasons, whereas 21.6% in warm and 38.4% in cool season show no desire for change (Fig. 9b). Despite the fact that the climate is dominated by high solar radiation all year round, the preference for more shade (Fig. 9c) is more pronounced in the warm season (84.5%) than in the cool season (58.6%). Respondents who desired more sun were 1.5% and 5.3% in the warm and cool seasons respectively. Respondents' desire for a less humid climate is more pronounced in the warm season (50.7%) than in the cool season (21.2%) though in the cool season 76.2% desire no change (Fig. 9d). It is worth noting that in this climate, the relative humidity is always high above 75% for most of the year but the vapour pressure is much higher during the warm season.

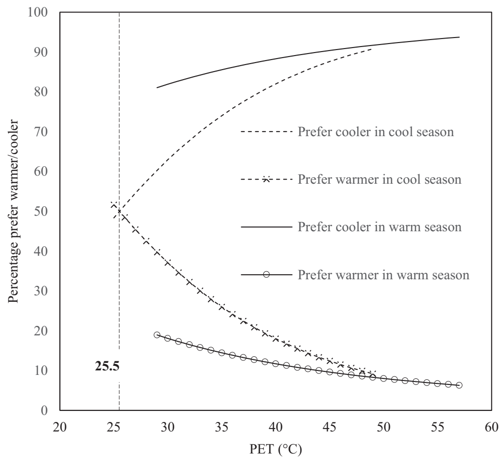

Fig. 8. The relationship between respondents' preference for warmth and PET in the warm and cool seasons by the Probit analysis.

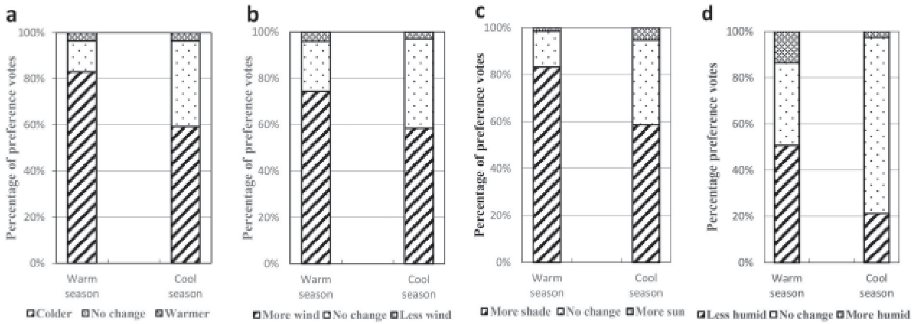

Fig. 9. Respondents' preference for microclimate variables in the warm and cool seasons, (a) air temperature, (b) air movement, (c) sun, and (d) humidity.

3.4. Coping strategies

The respondents' coping strategies during both seasons were examined based on the following adaptive behaviours: adjustment to their clothing, walking with two options: in shaded areas or with umbrella; drinking behaviour with two options: cold beverages or ambient temperature drinks and action of fanning (use of hand fan) as shown in Fig. 10. Among all adaptive behaviours, over 95% of the respondents prefer walking in shade and fanning in both the warm and cool seasons. Regardless of the season, seeking for shade when walking and fanning to enhance evaporative cooling were popular coping strategies.

On the other hand, the least used coping strategies were swimming and walking with umbrella being used by < 3% of the respondents. Respondents' behaviour of change of clothes was more observed in the cool season (66.1%) than the warm season (59.1%). Respondents' drinking habits show significant difference as 74.7% opted for cold drinks in the warm season compared to 51.4% in the cool season. The percentage of respondents who prefer ambient temperature drinks in the cool season is higher (48.6%) than in the warm season (25.3%).

4. Discussion

4.1. Informal and formal urban fabric dichotomy

As previously mentioned, the informal urban fabric morphology presents a number of challenges in terms of low air speed and

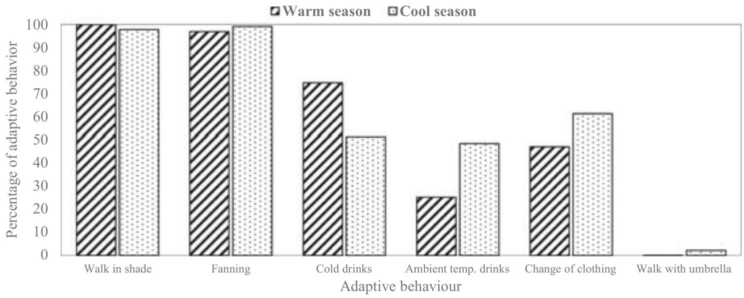

Fig. 10. Respondents' coping strategies to the outdoor thermal challenges in the warm and cool seasons.

excessive mean radiant temperatures (Yahia et al., 2018). Comparative analysis of the measurements from the formal/planned area of the city (House of Culture) and the site measurements revealed the distinctive characteristics of the warm and cool seasons and shed light on the respondents' responses as discussed later. In the warm season, there was no significant difference in terms of T_a and vapour pressure (Fig. 11); however, there was a notable difference in wind speed for all days. Informal urban fabric areas were found to have low wind speeds as compared to the formal urban fabric (Fig. 12). In the cool season, there is a significant decrease of vapour pressure and slight decrease of T_a when compared to the warm season (Fig. 11). The study found that the major distinction between the formal and informal urban fabric in terms of meteorological variables in this study is wind speed, which is higher in the former than the latter. Though the average wind speeds are low, a slight difference on the higher side found in formal urban fabric is thought to improve the thermal conditions (Ahmed, 2003; Cheng et al., 2012; Yin et al., 2012). It was not possible to compare the urbanites' thermal perception for the formal and informal urban fabric because a previous study by (Ndetto and Matzarakis, 2016) used the wind speed measurements from a meteorological station 11.5 km from the site. This study found that measured average wind speeds in the city centre are very low (< 2 m/s) compared to the one at the JNIA airport (4.8–5 m/s) used by Ndetto and Matzarakis (2016).

The study noted that the cool sensation votes "slightly cool" and "cool" coincides with much lower level of vapour pressure and a slight decrease in T_a. Despite the fact that there is a slight decrease in T_a in the cool season, the study noticed that T_a is still high as compared to other climates. The respondents' responses of "slightly cool" and "cool" expresses their high sensitivity to the slight decrease in T_a within the narrow T_a differences in the tropical savannah climates as observed in a study (Villadiego and Velay-Dabat, 2014). Though the measurements were taken in the critical times in terms of outdoor microclimate, the average temperatures are

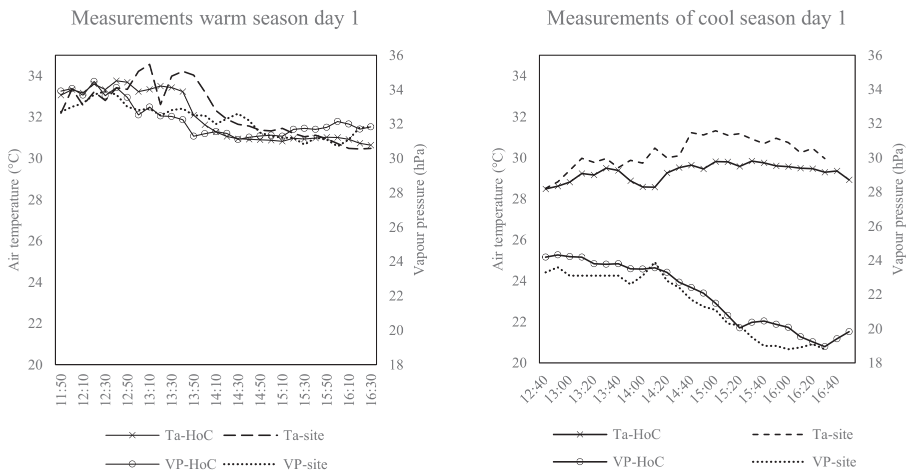

Fig. 11. Comparison of micrometeorological measurement (Ta & vapour pressure) in the warm and cool seasons, between formal House of Culture (HoC) and informal urban fabric (Kawe) during the measurement hours.

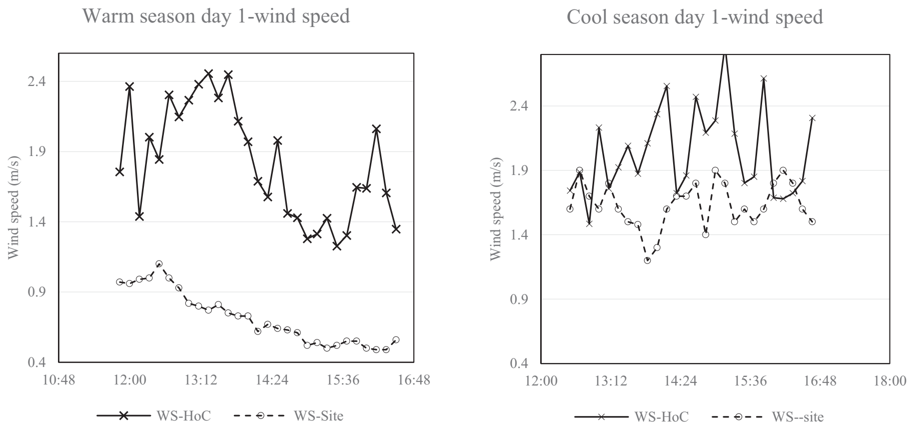

Fig. 12. Comparison of the wind speed (WS) in the warm and cool seasons between formal and informal urban fabric during survey campaign period in the city of Dar es Salaam, Tanzania.

usually high as shown in Fig. 3. Moreover, this study found no significant differences in T_{mrt} between the formal and informal urban fabric. This could be attributed to the fact that in both areas, the meteorological instruments were exposed to the open sky.

4.2. Urbanites' thermal perception

The urban morphology of informal settlements presents a complex structure, as it does not consist of regularly distributed dwellings (Sobreira and Gomes, 2001). Urbanites in informal settlements are experiencing an urban morphology characterised by dwellings, which are located haphazardly, rarely in conformity with ventilation and lacking physical harmony with the immediate surrounding buildings (Kombe and Kreibich, 2000). Analysis of thermal sensation votes (TSV) in the two informal urban fabrics, Kawe and Tandale, based on ASHRAE seven point scale shows no significant differences in the warm season with the majority (54% in Kawe and 58% in Tandale) of the respondents voting on the hot side of the scale (Fig. 4). This implies two major observations: first, the urbanites in the two informal settlements of the same category (high density, low rise residential) have similar response in TSV in the warm season. Second, the extreme microclimatic conditions during the warm season affects > 70% of the residents who voted from +2, warm and + 3, hot in both Kawe and Tandale. The cool season presents a thermally acceptable environment as the majority (over 90%) voted between −1, slightly cool and + 1, slightly warm. A previous study conducted in the formal urban fabric of Dar es Salaam (Ndetto and Matzarakis, 2016) also observed thermal relief in the cool season. However, the warm season in this study presents a huge difference compared to the Ndetto and Matzarakis study showing how extreme the thermal challenges faced by urbanites in the informal settlements are. It is worth to note as a limitation of the study that thermal sensation votes and micrometeorological measurements were taken in different days (Table 2); nevertheless, the respondents' thermal sensation vote pattern (Fig. 4) in the warm season depicts a similar trend. The results suggest that urbanites in informal settlements experience extreme thermal challenges regardless of location. Considering that 64% and 28% of the respondents are living and working within these informal settlements respectively, the results shed light to the outdoor thermal comfort challenges experienced.

Furthermore, this study investigates thermal acceptable ranges of urbanites in the informal urban fabric for the warm, cool, and combined (all year) seasons as presented in Fig. 6 and Table 3. Previous studies have shown that thermally acceptable ranges reveal different thermal requirements due to thermal adaptation in a specific climate (Johansson et al., 2014; Knez and Thorsson, 2006; Lin, 2009; Lucchese et al., 2016). In addition, regional climatic differences can be a contributing factor to the differences of the thermally acceptable ranges (Li et al., 2016). In this study, the thermally acceptable range for the warm and combined seasons were found to be 25.8–29.8°PET and 27.6–32.1 °C PET respectively. The previous study in the same city but in the formal urban fabric (Ndetto and Matzarakis, 2016) found acceptable ranges of 23–31 °C PET. In comparison, the thermally acceptable ranges of the informal urban fabric are higher and narrower when compared to the formal urban fabric. This implies that in the warm season which dominates the year (October–May), most of the time urbanites in these informal settlements suffer as they are outside of the thermal acceptable ranges (Fig. 5). Under such circumstances, any slight change in the outdoor thermal condition is expected to bring huge relief in the thermal perception as it can be observed in Fig. 5a where the majority voted within the comfort band during the cool season. The narrow ranges found in the informal urban fabric depict how these areas have limited adaptive options for the urbanites, which is contrary to the formal urban fabric with more adaptive options such as shaded street canopies and vegetation. In another study (Li et al., 2016) conducted in a residential community like this, the mentioned adaptive options were noted to improve thermal acceptability of residents. Other studies in the formal urban fabric of similar climates such as (Lin and Matzarakis, 2008; Lin, 2009; Lin et al., 2012; Ng and Cheng, 2012; Li et al., 2016; Johansson et al., 2018) found higher thermal acceptable ranges than those found in northern Europe (9–18 °C PET), (Kruger et al., 2013). Moreover, such studies found higher thermal acceptable ranges than the costal Mediterranean climate (20–25 °C, PET (Cohen et al., 2013). Since the analysis of data in this study indicates, that 91.5% of the respondents in the warm season and 92.8% in the cool season prefer to spend their free time outdoors rather than indoors, it is necessary to improve the outdoor thermal conditions of the informal settlements.

4.3. Thermal neutrality

In this study, the neutral PET index temperature for the warm, cool and combined seasons were determined; however, for comparison purposes, the neutral PET index temperature for warm season will be used due to the dominance of that season. The neutral index temperature for the warm season was found to be 27.5 °C and 27.7 °C PET for the Probit and regression techniques respectively (Fig. 7&Table 3). The slight difference between the two techniques shows that both of them are reliable. The neutral index temperatures are slightly different from a study carried out in the formal urban fabric in the same city (Ndetto and Matzarakis, 2016) which was 27 °C PET. However, authors are cautious to do a comparison and draw conclusions due to significant differences of wind speeds measured on the site for this study and the one used in the study by (Ndetto and Matzarakis, 2016). Moreover, when compared to a previous study in a similar warm-humid tropical savannah climate conducted in Guayaquil (Johansson et al., 2018), the neutral PET index temperature found here is higher by 2.1 °C PET. In addition, when compared to studies in the humid subtropical and tropical rainforest (Spagnolo and de Dear, 2003; Lin, 2009; Liu et al., 2016) the neutral index temperature in the warm season is even higher. In these studies, the neutral PET index temperature in warm season was found to be 22.9 °C for Sidney (Spagnolo and de Dear, (2003)) and 25.6 °C for Taichung (Lin, (2009)). Since the warm season dominates the year in the city of Dar es Salaam, result shows adaptation and higher tolerance to high PET index temperatures of urbanites in the informal settlements.

As experienced in other studies, differences of neutral PET index temperatures between seasons were observed (Table 3). For example, (Hwang et al., 2010; Hwang et al., 2011; Assis and Nikolopoulou, 2016; Liu et al., 2016) compared neutral PET index temperatures for two seasons and found that people had different thermal perception in each season. In the humid subtropical climate, which experiences winter, observed differences in the neutral PET index temperatures between warm and cool seasons is associated with the effect of seasonal adaptation of thermal comfort, due to both psychological and behavioural adaptation to variations in the microclimate as pointed out by Lin et al., (2011).

In this study, however, the neutral index temperature in the cool season (39.5 °C PET) is higher than in the warm season (27.5 °C PET) despite the fact that in the cool season (June–September) over 90% of the respondents voted within the three central categories. The fact that urbanites enter in a cool season after a long period of high thermal stress, any small change in the outdoor thermal conditions could make them experience a huge relief and psychologically influence their thermal sensation votes. Contrary to the previous study by (Ndetto and Matzarakis, 2016) in the formal urban fabric where the average clothing values were 0.32–0.39 (beach) and 0.43–0.44 (city centre park), this study found average clothing of 0.52 for both seasons. The possible reason for the difference in clothing values between urbanites' in the formal and informal urban fabric could be because in the latter, urbanites are more conservative in the style of dressing. Since the average clothing value was the same in all seasons, it can be argued that the difference in neutral PET index temperatures is the result of the effect of seasonal adaptation on thermal comfort and that it is more of a psychological than behavioural adaptation. Similar findings of neutral PET index temperatures being higher in the cool season than in the warm season were observed in other studies (Spagnolo and de Dear, 2003; Johansson et al., 2018).

4.4. Thermal preference

The preferred PET index temperature is the temperature that people want (Lin, 2009) and depicts expectation of the respondents from the thermal environment they experience. This study determined the preferred PET for the cool and combined seasons only (Table 4) as the majority of respondents votes were skewed to the hotter side of the thermal preference scale (Fig. 7). The fact that the preferred PET for both the combined season (21.5 °C) and the cool season (25.5 °C) is considerably lower than the neutral PET index temperature shows that urbanites felt comfortable at higher PET index temperatures than they usually desire. This is in alignment with findings of previous studies (Lin, 2009; Yang et al., 2013a; Johansson et al., 2018). It is worth pointing that for preferred temperature, the results were not statistically significant at 95% confidence level as noted in Table 3.

4.5. Preference for microclimatic variables

Preference for microclimatic variables shows the expectations of respondents of the outdoor thermal conditions. In this study, the question was, ‘how would you prefer the climate in this place?’ Respondents were given options of preference on four microclimatic variables as indicated in Appendix 1 and the results were compared for the warm and cool seasons. The high percentage of respondents (83%) who prefer a colder environment (Fig. 9) in the warm season reflects the thermal sensation votes (Fig. 4) in both Kawe and Tandale in which > 70% voted in ‘warm’, +2 and ‘hot’, +3 category. Despite the fact that in the cool season only 10% of the respondents had their thermal sensation votes outside the comfort categories ‘slightly warm’, −1, ‘neutral,’ 0, and ‘slightly warm,’ +1; almost 60% of respondents prefer a colder environment. This depicts respondent's high sensitivity to the air temperature in both the warm and cool seasons. This agrees with a previous study (Villadiego and Velay-Dabat, 2014) which showed that people in the warm humid tropical savannah (Af) are highly sensitive to very small variations in air temperature.

On the other hand, sensitivity to solar radiation shows close similarities with air temperature as 84.5% and 58.6% of the respondents prefer more shade in the warm and cool seasons respectively (Fig. 9c). This shows the necessity of shade as a means of regulating the outdoor thermal environment. It can be argued that due to the nature of the tropical savannah (Af) climate, both T_a and solar radiation have similar influences in the warm and cool seasons. This is contrary to the humid subtropical climate where Lin, (2009) found that PET and T_{mrt} strongly influence the number of people visiting the square in the hot season compared to air temperature but in the cool season, the T_a was a determining factor on the use of the square.

It is known that tropical areas are often characterised by low wind speeds, especially when they are affected by the intertropical convergence zone (ITCZ) (Johansson, 2016). The situation becomes more challenging in informal settlements due to their morphological structure. Previous studies (Ahmed, 2003; Ng et al., 2012; Yin et al., 2012) found increased air movement to be an important factor in mitigating the heat stress in the urban area and the percentage of respondents that expressed neutral thermal perception increased gradually with increased air movement. In the warm season, 74.3% of respondents showed preference to more wind while only 26% prefer no change and in the cool season, 58.4% prefer more while 38.4 prefer no change in wind. More wind dissatisfaction in the warm season may be attributed to high vapour pressure experienced during the survey (Table 2) with an average of 30.6 hPa compared to 20.8 hPa in a cool season. The high vapour pressure had negative impact on the expected positive influence of wind speed on the convective heat loss from the body.

Respondent's preference to humidity is to be taken with caution as the interpretation of the term was challenging for many of the respondents. In warm humid climates, high levels of relative humidity and fairly high levels of air temperature are experienced as uncomfortable since cooling of the body through evaporation is restricted (Johansson, 2016). In the warm season, the majority of respondents (50.7%) prefer less humidity compared to the cool season (21.2%). It has to be noted that the relative humidity is over 65% almost throughout the year. In the cool season, 76.2% prefer no change of the humid conditions; however, almost 60% indicated that they prefer more wind. This is contrary to the natural pattern of sensation; it could suggest that respondents were voting based on the general satisfaction of changes (reduction of air temperature) after a long period of warm season. Despite the fact that thermal perception is linked to climate conditions, an holistic assessment of the influence of climatic variables is necessary as no single climatic variable on its own can explain thermal perception (Villadiego and Velay-Dabat, 2014).

4.6. *Coping strategies*

Coping strategies to the outdoor thermal discomfort conditions comprise of adaptive measures opted by respondents in various occasions. Adaptation is defined as ‘the gradual decrease of the organism's response to the repeated exposure to a stimulus’ (Nikolopoulou et al., 1999), and can be physiological, behavioural, and psychological. Respondents in this study have pointed out some of the behavioural adaptation measures used such as change of clothing, moving in space and diet. There was no major difference between males and females in terms of use of various coping strategies; however, differences between seasons were observed based on certain coping strategies. A tendency to seek shading areas during a walk and the use of hand fanning such as a newspaper is used by over 95% of respondents during high thermal stress conditions in both seasons. Moreover, cold drinks are more widely used in the warm season (75%) than in cool season (51.4%). Such behaviour is observed in other studies (Yang et al., 2013a; Tung et al., 2014; Li et al., 2016; Watanabe and Ishii, 2016; Johansson et al., 2018). Within the informal urban fabric, this behaviour involves seeking shade under a limited number of available trees or man-made shading devices and often the house veranda since there are no street canopies. The study found that both front and rear verandas were used differently depending on the position of the solar radiation; however, traditionally females commonly use the rear veranda. Despite the fact that studies (Tung et al., 2014; Johansson et al., 2018) found the use of umbrella as shading to be common among respondents, this study found that it is below 2%. On the same note, the study found that the use of umbrella for solar shading was not common.

The tendency to change clothing is more in the cool season (61.3%) than in the warm season (47.2%). The average clothing value is slightly higher than that of Ndetto and Matzarakis (2016). However, Ndetto and Matzarakis (2016) also found slight differences in clothing values between park and beach but noted that the majority of the local people tend to put on similar kind of clothing materials irrespective of the change of weather conditions. Similarly, in the tropical rainforest climate (Af), studies have shown that there were no differences in clothing values during different seasons of the year (Makaremi et al., 2012; Johansson et al., 2018;). On the contrary, significant differences in clothing values were found in the humid subtropical climates, which is associated with seasonal variations (Hwang et al., 2010; Lin et al., 2011; Lin et al., 2012), where clothing insulation increased with decreasing index temperature and vice–versa.

The fact that informal settlements have very low wind speed and high vapour pressure in a dominating warm season when compared to the cool season with a slight decrease in T_a accompanied with significant decrease of vapour pressure contribute to both physiological and psychological effect to the urbanites. The high sensitivity of the urbanites to the slight decrease of T_a supports the finding by (Villadiego and Velay-Dabat, 2014) that people in warm humid climates are sensitive to a very small change in T_a. In addition, majority of respondents were at their place of living, which consists of a huge difference to the Ndetto and Matzarakis (2016) study that was carried out in a beach and a park in terms of dress code and clothing values. The lower clothing values found in their study when compared to this study could perhaps indicate urbanites' shift of mind set when they dress for beach or offices. It can be argued that apart from cultural dresses, respondents in the tropical savannah climate of Dar es Salaam tend to dress casually. Nevertheless, people who go to the beach or to offices tend to dress accordingly.

Declaration of Competing Interest

There is no conflict of interest in this submission.

Acknowledgment

The funding source is Swedish International Development Cooperation Agency (Sida) based in Stockholm, Sweden, supported this study financially.

Appendix A. Appendix 1

Outdoor Thermal Comfort Questionnaire

Place: ....
Date: ....
Time: ....

1. Personal information

Sex: ☐ Male ☐ Female

Age: ☐ ≤ 20 ☐ 21-35 ☐ 36-50 ☐ 51-65 ☐ 66-80 ☐ >80

☐ Live in the neighborhood ☐ Work in the neighborhood ☐ Neither of them

2. What is the reason for being in this place?

☐ On my road to home/work/school/etc ☐ See other people/Relax/Get fresh air

☐ Both ☐ Other reason …………………………………………..….

3. How often do you pass by this place?

☐ Daily ☐ A few times/week ☐ A few times/month ☐ Rarely ☐ First time

4. How long time have you been outdoors today?

☐ Less than one hour ☐ Between 1-2 hours ☐ Between 2-3 hours ☐ More than 3 hours

5. How did you spend the last half hour?

☐ Sitting ☐ Standing ☐ Walking ☐ Other …………………………..

6. How do you feel in this place right now?

Cold	Cool	Slightly cool	Comfortable	Slightly warm	Warm	Hot
☐	☐	☐	☐	☐	☐	☐

7. How do you sense the climate in this place?

Temperature:	☐ Warm	☐ Neutral	☐ Cold
Sun:	☐ Sunny	☐ Neutral	☐ Shady
Humidity:	☐ Humid	☐ Neutral	☐ Dry
Wind:	☐ Windy	☐ Neutral	☐ Calm

8. How would you prefer the climate in this place?

Temperature:	☐ Warmer	☐ No change	☐ Colder
Sun:	☐ More sun	☐ No change	☐ More shade
Humidity:	☐ More humid	☐ No change	☐ Less humid
Wind:	☐ More wind	☐ No change	☐ Less wind

9. Where do you prefer to spend your free time?

☐ Indoors ☐ Outdoors ☐ Other ……………………………………………

10. What type of clothing do you wear?

Shirt	*Trousers*	*Shoes*	*Traditional*	*Head*	*Other*
☐ Short sleeves	☐ Shorts/skirt	☐ Sandals	☐ Kanzu	☐ Hat	☐ .... ……..
☐ Long sleeves	☐ Long trousers	☐ Shoes	☐ Khanga	☐ Parasol	………………..
☐ Singlet top			☐ Masai dress		

11. How do you cope with extreme outdoor weather?

Clothing	*Sitting/Walking*	*Drinking*	*Relaxing*	*Other*
☐ Change clothing	☐ On shaded areas	☐ Cold fluid	☐ Swimming	☐ .... ……..
☐ Remove clothing	☐ With Umbrella	☐ Normal fluid	☐ Fanning	………………..

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Paper III

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Urbanites' outdoor thermal comfort in the informal urban fabric of warm-humid Dar es Salaam, Tanzania

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ABSTRACT

In warm humid tropical climates, the outdoor environment defines the lives of the majority of the population in terms of social and economic aspects. Improvement of the outdoor thermal environment encourages social and economic prosperity of the urbanites. This paper explores urbanites' thermal comfort in the informal urban fabric of warm humid Dar es Salaam, Tanzania. Simultaneously, the study conducted micrometeorological measurements and a questionnaire survey consisting of 1541 respondents for both the warm and cool seasons. The thermal indices, Standard Effective Temperature (SET*), Universal Thermal Comfort Index (UTCI) and Physiological Equivalent Temperature (PET) were calculated. Results show that urbanites of the informal urban fabric areas experience both narrower and higher thermal comfort ranges when compared to both similar climates and other types of climate in the formal urban fabric context. Thermal acceptable ranges were found to be 30.2 − 32.5 °C and 23.4 − 27.4 °C for UTCI and SET* respectively. Despite the fact that the results showed the high adaptive capacity of the urbanites, they also revealed the urbanites' tolerance to high thermal index temperatures due to the limited adaptive options available within the informal urban fabric morphology. The study findings could contribute significantly to the upgrading of informal settlements.

1. Introduction

In the past decades, cities in developing countries have been experiencing rapid urbanisation, mostly caused by population influx from rural areas. This urbanisation refers to expansion in urban population and scale and the corresponding series of socio-economic changes (Wang, Hui, Choguill, & Jia, 2015). One of the results of this urbanisation is the formation of informal settlements also referred to in this article as informal urban fabric areas, which dominate the image of many cities in the developing countries (Wekesa, Steyn, & Otieno, 2011). Globally, one in eight persons lives in slums, and, in developing countries, an estimated 30 % of urban residents lived in poor informal settlements in 2014 (Un-Habitat, 2016). In addition, it is estimated that 881 million urbanites lived in the informal settlements in 2014 as compared to 689 million in 1990 (Un-Habitat, 2015). Notably, the speed of urbanisation in these cities outweighs the urban planning capabilities of the same. Urbanites residing in informal urban fabric areas of these cities face many challenges such as poor or lack of urban infrastructure like roads as well as services like water and electricity to mention a few (Bank, 2013).

Dar es Salaam[1] is a tropical city located in the sub-Saharan region with a growth rate of 5.6 % (NBS, 2013). As for the majority of the tropical cities, much of the urbanisation is taking place with little economic development (Hsieh, 2014) primarily due to demographic transition where economic and other considerations hold secondary influence (Dyson, 2011). The city's planning agencies did not keep up with the rapid expansion and urban transition, which led to the growth of spontaneous settlements of different categories (Peter & Yang, 2019). This urbanisation leads to growth of informal settlements characterised by dwellings, which are located haphazardly, rarely providing adequate ventilation and lacking physical harmony with the immediate surrounding buildings (Kombe & Kreibich, 2000). This is contrary to the call by United Nations Agenda 2030 for enhancing sustainable urbanization and human settlement planning in all countries by reduction of the adverse per capita environmental impact of cities. It is estimated that informal settlements accommodate up to 85 % of the (urbanites) population (Kironde, 2006). Presented challenges are physical in nature and obvious to the majority; what is not obvious and missed attention

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of the research community is the question on the state of outdoor thermal comfort of this population.

Previous research (Fang et al., 2019; Johansson, Yahia, Arroyo, & Bengs, 2018; Kruger, Drach, & Broede, 2017; Li, Zhang, & Zhao, 2016; Watanabe & Ishii, 2016; Yahia, Johansson, Thorsson, Lindberg, & Rasmussen, 2018,) on outdoor thermal comfort in warm humid climates have provided substantial information on the urbanites' thermal perception, thermal comfort limits, and psychological influence of outdoor microclimate within the formal urban fabric areas. However, the informal urban fabric in tropical warm humid climates presents its own challenges posed by its morphological structure. According to Wekesa et al. (2011), the morphological structure of informal settlements not only vary widely across the city depending on the income levels of the urbanites, but also carry a major character of being built without legal tenure and do not follow established building and planning regulations. In addition, the geometric structure of the informal urban fabric is complex (Sobreira & Gomes, 2001) and poses challenges in terms of the outdoor thermal environment. It typically develops organically and in an irregular pattern with footpaths as the form of access in major part and consists of irregularly distributed buildings. On re-thinking of outdoor thermal comfort in warm humid climates, it is vital to consider urbanites residing in the informal urban fabric as they represent the majority in many cities in tropical regions. Baruti, Johansson, and Astrand (2019) postulated that in the absence of empirical study on outdoor thermal comfort in the informal urban fabric areas, results from formal urban fabric areas can easily be assumed to apply in the informal urban fabric areas and lead to lack of interest to explore the latter. Notably, only a few studies (Kakon, Mishima, & Kojima, 2009; Sharmin, Steemers, & Matzarakis, 2015; Yahia et al., 2018) have investigated informal settlements' outdoor thermal environment. Moreover, the focus in these studies were on simulation and did not investigate the state of thermal comfort. Thus, little is known on the subjective thermal comfort of the urbanites residing in these areas.

The major objective of this study is to investigate subjective thermal comfort of urbanites in informal settlements in a warm humid climate of Dar es Salaam. Contrary to previous studies, this study takes a shift from traditional locations, (e.g., squares, parks, train stations, leisure areas-beaches, and semi-outdoor spaces) which are normally found in formal/planned parts of cities and dwell in investigating the urbanites thermal conditions in their residing areas. The informal urban fabric, which represents the major part of urban growth in the majority of cities in developing countries is the focus of this study. The study investigated the following aspects of outdoor thermal comfort:

1 urbanites' thermal sensation during warm and cool seasons;
2 the influence of micrometeorological variables on outdoor thermal comfort in the informal urban fabric; and
3 the thermally acceptable ranges/limits, neutral temperatures and preferred temperatures for the warm, cool and combined seasons.

2. Materials and methods

2.1. Climate and studied locations

The city of Dar es Salaam (6°51′S, 39°18′E) is located along the coast of the Indian Ocean (Fig. 1). The annual mean maximum temperature varies between 29 and 32 °C, while the annual mean minimum temperature varies between 19 and 25 °C (refer Table 2). The highest temperatures are experienced in December - March, while the cool period with relief in thermal comfort is between June and September. Relative humidity remains high; it is on average about 75 % most of the time, but it may vary from 55 to almost 100 %. According to (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006), Dar es Salaam is categorised as warm humid tropical savannah (Aw). Based on the passages of the inter-tropical convergence zone (ITCZ), two seasons can be distinguished; the northeast monsoon between March and October, and the southeast monsoon between October and March (Iversen, Myklevoll, Lwiza, & Yonaz, 1984; Jonsson, Bennet, Eliasson, & Selin Lindgren, 2004).

According to Iversen et al. (1984), the NE winds are lighter, while the SE winds are stronger. March and July were the months selected to represent the warm and cool seasons respectively in this study. Table 2 presents the micrometeorological measurements for the city of Dar es Salaam for a period of 10 years from 2000 − 2009.

The two selected field survey locations were Kawe and Tandale, which are 1.5 and 7.2 km respectively from the coast of Indian Ocean. Field surveys were carried out in the streets of the two informal urban fabric neighbourhoods in which the main street, which acts as the main access to the inner part of the neighbourhood, was chosen. The reason for choosing Kawe and Tandale is the fact that they represent a category of informal settlements known as consolidated high density, low rise as identified in Lupala (2002) and the fact that they represent a larger part of the residential settlements where urbanites reside in Dar es Salaam city (Lupala, 2002). The typical character of these neighbourhoods is narrow and winding streets due to compactness of the building structures. Large sections of the housing areas within these settlements are only accessible by footpaths. Fig. 1 shows the geographical location of the study areas. In addition, Fig. 2 shows the studied locations with the positions where micrometeorological measurements were taken. Red dot marks the area where a meteorological station was positioned. The instruments used were fully exposed to solar radiation.

Kawe is located at latitude 6° 44′ 17″ and longitude 39° 13′ 39″, 1.5 km from the Indian Ocean and 11.8 km from the central business district (CBD). The measurement equipment was placed on a pedestrian path at the junction of the market street (Fig. 2). Tandale is located at latitude 6° 47′ 36″S and longitude 39° 14′ 39″ E, 7.2 km from the CBD and 5 km from the coast of Indian Ocean. In this area (Tandale), the main street was chosen.

2.2. Micrometeorological measurements

Both the micrometeorological measurements and the questionnaire surveys were conducted during the warm season (March 2017) and the cool season (July 2017). The fieldwork survey took place for 8 days. There was rainfall, which lasted for 25 min in day 3 in the cool season during which measurements were stopped. In Kawe, the street was oriented northwest-southeast while in Tandale it was oriented in the northeast-southwest direction. Measurements took place from 11:00 am to 5:30 pm. It is worth mentioning that the measurements took place in different days in the two fieldwork areas. A mobile meteorological station, positioned on a tripod, took measurements of air temperature (T_a), relative humidity (RH), wind speed (ν) and globe temperature (T_g) directly from the field. The measured microclimatic variables, measurement instruments, and their accuracy are presented in Table 1. The mean radiant temperature (T_{mrt}) was calculated as described in Section 2.4.

A data logger (Campbell CR800) was used to connect the sensors in which 1-minute averages were sampled. The measurement were taken at the height of 1.1 m above the ground which corresponds to the to the average height of the centre of gravity of adults (Mayer & Höppe, 1987), with the exception of a wind speed, which was measured at 1.5 m height by the use of a two-dimensional ultrasonic sensor (Gill windsonic),which detects speed down to 0.02 m/s. However, the Gill windsonic measures only the horizontal component of the wind speed. Since the urban wind pattern is often irregular and includes vertical movements, there is a possibility that the wind speed was slightly underestimated. The wind speed at 1.1 m was determined as (Aynsley, Melbourne, & Vickery, 1977)

$$\nu_{1.1} = \nu_{1.5} \times \left(\frac{1.1}{1.5}\right)^{\alpha} \tag{1}$$

where $\nu_{1.1}$ is the wind speed at 1.1 m, $\nu_{1.5}$ is the wind speed at 1.5 m and

Fig. 1. Study areas–Kawe (along the coast) and Tandale in the city of Dar es Salaam. Image edited from (Mboera et al., 2016).

α is the mean speed exponent, which depends on the roughness of the ground (e.g. $\alpha = 0.20-0.25$ for urban low-rise and density and $\alpha = 0.29-0.35$ high-rise office and apartment tower clusters (Oke, Mills, Christen, & Voogt, 2017). In this study $\alpha = 0.24$ was used. The formula is valid for an open terrain and it might be less accurate in the urban context. However, since the difference in wind speed at 1.1 and 1.5 m are small, the wind speed is assumed to be accurate.

The sensor for air temperature and humidity (Rotronic Hydroclip S3) had a long response time and therefore, 5-minute interval was allowed prior to the beginning of the measurements. A white, naturally ventilated radiation shield as shown in Fig. 2b covered the sensor.

2.3. Calculation of the mean radiant temperature

The mean radiant temperature (T_{mrt}) was calculated from measured values of T_g, T_a and ν based on Eq. (2) and procedures according to (Thorsson, Lindberg, Eliasson, & Holmer, 2007). The following formula was used for determining T_{mrt}:

$$T_{mrt} = \left[(T_g + 273)^4 + \frac{1.335 \times 10^8 \nu_a^{0.71}}{\varepsilon D^{0.4}} \times (T_g - T_a) \right]^{0.25} - 273.15 \quad (2)$$

where T_g = globe temperature (°C), ν_α = wind speed (m/s), T_a = air temperature (°C), D = globe diameter (mm) and ε = globe emissivity.

The colour of the globe was grey with a diameter of 40 mm. A small lightweight globe thermometer has a time constant of about 5 min (Nikolopoulou, Baker, & Steemers, 1999), which is much shorter for the standard indoor 150 mm copper globe thermometer having a time constant of 20 − 30 min (ISO-7726, 1998). T_{mrt} calculated in this way is very sensitive to variations in wind speed; a sudden change in wind speed will result in an incorrect T_{mrt} (Johansson, Thorsson, Emmanuel, & Krüger, 2014). In order to reduce the sensitivity to variations in wind speed, 10 min average of wind speed and 5 min average of T_a and T_g were used in the calculations of the T_{mrt}.

2.4. Questionnaire survey

In each location, micrometeorological measurements were conducted simultaneously with questionnaire surveys. Survey campaigns

Fig. 2. Study areas, Kawe (a&b) and Tandale (c&d).

Table 1
Measured variables, instruments, and accuracy of the instruments. Air temperature (T_a), globe temperature (T_g), relative humidity (RH), wind speed (ν), wind direction (ν_d).

Variable	Instrument	Accuracy
T_a	Rotronic hydroclip S3	± 0.3 % °C
T_g	Pt100 in a grey plastic ball (D = 40 mm)	± 0.3 °C at 0 °C
RH	Rotronic hydroclip S3	± 1.5 % RH
ν, ν_d	Gill windsonic anemometer	± 2 %@ 12 m/s

were conducted in both the warm season (March) and the cool season (July) for Kawe and Tandale neighbourhoods. 1541 respondents were interviewed, 746 during the warm season and 795 respondents during the cool season. Locations where majority of people pass and do their daily activities (small commercial activities) were chosen. Analysis of character of respondents shows that, in terms of gender, there was an equal representation of respondents in which 50.6 % were male and 49.4 % were females. In terms of age group, the middle-aged group (21–50 years) comprised 78 % of the total respondents with 53.7 % of respondents bearing the age of 21 − 35 years. The majority of the respondents (46.4 %) spent more than 3 h outdoors prior to the survey while those who spent between 1 − 3 hours were 39.6 %. Moreover, the dominant activity of respondents during the survey was walking (45.6

Table 2
Monthly mean temperatures, relative humidity and solar irradiance, and wind speed in Dar es Salaam.

	Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sep	Oct	Nov	Dec
Max. Mean. Temp.(°C)	31.3	31.7	31.3	29.4	29.6	28.4	28.6	28.8	29.2	30.5	30.5	31.4
Min. Mean. Temp(°C)	24.8	24.4	23.8	22.6	21.9	20.2	19.5	19.3	19.7	21.3	22.7	24.5
Mean. Temp (°C)	28.1	28.0	27.58	25.9	25.8	24.3	24.1	24.0	24.5	25.9	26.6	27.9
Avg. Relative Humidity (%)	77	78	82	87	82	80	77	78	77	77	81	79
Avg. Vapour pressure (hPa)	29.3	29.5	30.2	29.1	27.2	24.3	23.1	23.3	23.7	25.7	28.2	29.7
Avg. Wind Speed (m/s)	4.8	4.1	2.8	2.5	2.9	3.4	3.4	2.9	2.9	3.0	3.0	4.0
Solar radiation (MJ/m^2 day)	19.5	19.7	17.7	14.3	15.6	15.7	16.0	17.3	18.5	19.5	21.0	20.1

%) followed by sitting (34 %) and standing (20.5 %).

Respondents were asked to complete questionnaire surveys for estimation of the subjective thermal comfort. All respondents were volunteers. The questionnaire was translated into the Swahili language, the English version is attached as Appendix A. The ASHRAE 7-point scale for thermal sensation votes was used. The choice of the 7-point scale was reached as a result of the piloting study which was conducted with the objective of testing the preferable scale. A seven-point scale has also been used in several other similar studies (Hwang & Lin, 2007; Ndetto & Matzarakis, 2016; Spagnolo & De Dear, 2003).

Respondents were requested to respond to their thermal sensation and preference on variables of atmospheric weather conditions, i.e. air temperature, wind speed, sun and humidity using a 3-point scale (Mcintyre, 1980), as shown in Appendix 1. Moreover, the survey questionnaire comprised questions about gender, age, time spent outdoors, activity, reason for being in the place as well as coping strategies during extreme weather conditions. The type of clothing and activity were observed by the interviewer and then chosen from a predefined list. Activities before the interview were defined as sitting, walking, and standing; however, during the interview, respondents were normally standing. The exercise took 4 − 6 min per questionnaire.

The team conducting the survey consisted of the main author and six graduates from the School of Architecture Construction Economics and Management at Ardhi University. Among them, there were 3 females and 3 males. The same team that participated in the pilot study in August 2016; therefore, they were familiar with the exercise.

2.5. Thermal comfort investigation

2.5.1. Thermal indices used

For several reasons, three indices were chosen to assess the outdoor thermal comfort in this study. These indices include, the Standard Effective Temperature (SET*), the Universal Thermal Climate Index (UTCI), and the Physiological Equivalent Temperature (PET). SET* was chosen as it has been widely used in outdoor thermal comfort studies in warm humid climates (JEONG, PARK, & SONG, 2016; Johansson et al., 2018; Watanabe, Nagano, Ishii, & Horikoshi, 2014; Xi, Li, Mochida, & Meng, 2012; Zhao, Zhou, Li, He, & Chen, 2016) and it incorporates clothing and metabolic activity of the respondents. UTCI is not yet widely used; however, it is universal and it is theoretically supposed to work in all climates. In addition, UTCI is highly accurate in replicating the human dynamic thermal response under a wide range of thermal environments (Fiala, Lomas, & Stohrer, 2001). Moreover, (Watanabe et al., 2014) and (Kruger et al., 2017), have proved its applicability in warm-humid regions. PET was chosen as it is the most used thermal comfort index (Chen & Matzarakis, 2014; Coccolo, Kampf, Scartezzini, & Pearlmutter, 2016; Johansson et al., 2014) and frequently used in warm-humid regions (Binarti, Koerniawana, Triyadia, Utamic, & Matzarakis, 2020). The wide use of PET globally allows comparison with other studies. Detailed descriptions of these indices are found in (Pickup & De Dear, 2000) for SET*; (Jendritzky, Havenith, Weihs, & Batchvarona, 2009; Jendritzky, De Dear, & Havenith, 2012) for UTCI and (Mayer & Höppe, 1987) for PET. SET* was calculated using Win-Comf software (Fountain & Huizenga, 1996). UTCI was calculated using BioKlima (Blazejczyk, 2017) while PET was calculated using RayMan (Matzarakis, Rutz, & Mayer, 2007).

2.5.2. Thermal comfort ranges

Thermal comfort ranges were calculated using linear regression based on a MTSV boundary of -0.5 to + 0.5 which theoretically coincide with 90 % thermal acceptability (Ashrae, 2004). In addition, the comfort limits for 20 % unacceptability were calculated using the method by (Lin, 2009). The percentage of unacceptability was calculated in each 1 °C bin of respective thermal index by using a method by (De Dear & Brager, 1998). Further, the respondent's MTSV votes falling into central categories (− 1, slightly cool; 0, neutral; 1, slightly warm) of the thermal sensation scale were considered as thermally acceptable votes (Lin, 2009; Spagnolo & De Dear, 2003).

2.5.3. Neutral and preferred index values

In this study, neutral temperature was determined by two methods. First, bins for thermal indices were created at an interval of 1 °C. Then, the fitted regression equations resulting from mean thermal sensation votes and thermal index values were also used to determine the neutral temperature (MTSV = 0). The second method used to determine the neutral index temperature was the Probit method (Ballantyne, Hill, & Spencer, 1977; Spagnolo & De Dear, 2003). The Probit method was also used to determine preferred index temperature values. In addition, binning method (regression) was later used to determine the relationship of meteorological variables (T_{mrt}, T_a, and VP) and MTSV. First, bins for T_{mrt}, T_a, and VP were created at intervals of 3 °C, 0.1 °C and 0.4 hPa respectively. Then, the fitted regression equations resulting from mean thermal sensation votes and microclimatic variables were made.

2.5.4. Statistical tests

In this study, two main statistical tests were conducted; these are Chi-square test of independence and independent sample *t*-test. In both statistical tests, the confidence interval used was 95 % implying significance level of 0.05. In this sense, SPSS statistical analysis software was used.

3. Results

3.1. Seasonal and spatial microclimatic differences

Table 3 presents a statistical summary of the micrometeorological measurements during the warm and cool seasons. The warm season has higher T_a, T_{mrt}, and vapour pressure and slightly lower wind speed compared to the cool season. Vapour pressure was calculated based on measurements of relative humidity and T_a. There is significant drop of vapour pressure in the cool season. Similarly, wind speeds were very low when measurements were taken in both seasons (Fig. 3); this could be due to the nature of informal urban fabric areas in which compactness of building structures is very high. It is worth noting that most of the measurements were taken from 11:00 h to 16:00 h, which is considered as peak hours. In addition, the measurements were taken in different days in the study areas.

Fig. 3 presents the measurements in terms of the season, site, day, and period; T_{mrt} was calculated as per Eq. (2). For clarity of Fig. 3, the warm season is presented by acronym WS and the cool season by CS. In both seasons, T_a was stable for most of the time while T_g follows T_{mrt}. Nevertheless, significant variations of T_{mrt} were noticeable especially on the third day of the cool season. The condition is attributed to dense cloud associated with the light rainfall that lasted for about 20 min in which measurements were stopped. In Fig. 3a, the dramatic decrease of T_{mrt} and T_g in some days is associated with an increase in the cloud cover which results in the decrease in radiation intensity and leads to

Table 3
Micrometeorological measurement statistical summary for the measured warm and cool days.

Measurement	Warm season			Cool season		
	Mean	Min	Max	Mean	Min	Max
Air temperature (°C)	32.4	23	34.6	30.4	28.4	32.4
Globe temperature (°C)	36.9	22.4	45.1	33.4	27.8	40
Mean radiant temperature* (°C)	54.3	19.9	80.6	47.3	22.6	75
Relative humidity (%)	63.9	49	73.9	48.1	36.7	60.9
Vapour pressure (hPa)	30.9	15.1	34.4	20.8	165	24.3
Wind speed (m/s)	1.1	0.44	2.1	1.3	0.5	2.1

* Calculated from the measurements.

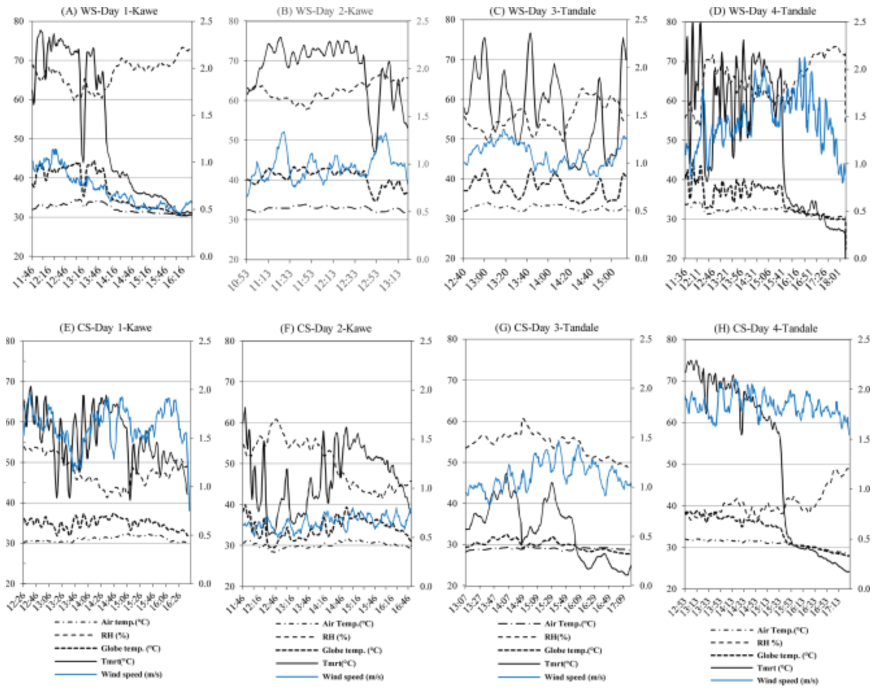

Fig. 3. The measurements in the warm season (WS) for day 1-4 (a-d) and the cool season (CS) from day 1-4(e-h) in Kawe and Tandale.

the decrease of T_{mrt}.

3.2. Subjective thermal comfort

3.2.1. Link between thermal sensation votes and meteorological variables

The influence of the meteorological variables on the thermal sensation of the respondents was examined through meteorological measurements and MTSV. Fig. 4 shows the relationship between the meteorological variables T_{mrt}, T_a, vapour pressure, and MTSV. Dashed vertical lines indicate maximum T_{mrt} and T_a where respondents' votes are logical. According to Fig. 4a and b, both T_{mrt} and T_a show stronger relationship with MTSV in the warm season than in the cool season. The

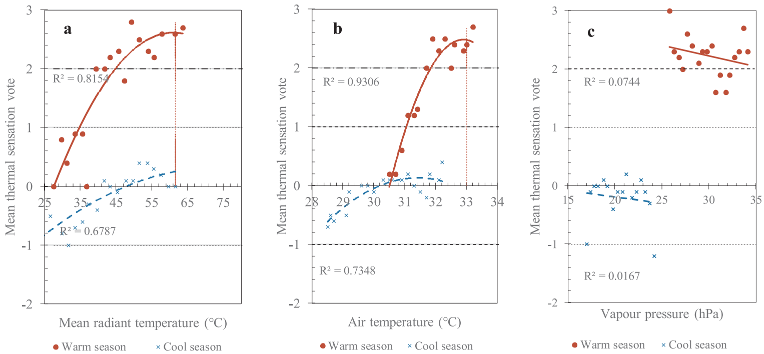

Fig. 4. The relationship between MSTV and meteorological variables for the warm and cool season.

other meteorological variables, wind speed and vapour pressure, show weak relationship with thermal sensation votes in both warm and cool seasons. The high amount of vapour pressure experienced in the warm season relates to the thermal sensation votes categories of +2 (warm) and +3 (hot). There was no meaningful relationship between respondents' MTSV and vapour pressure as shown in Fig. 4c.

Respondents' MTSV relationship with T_{mrt} and T_a is further explored in Fig. 4a and b in terms of percentage of respondents within the limits of thermal comfort specifically in the dominating warm season. In the warm season, only 28.1 % of the respondents voted in the acceptable range (−1 to +1) when the range of T_a was 30.5–31.1 °C. Likewise, the remaining 71.8 % of respondents voted in a warm range +2 (15.6 %) to +3 (56.1 %) when T_a range was 31.2–34.6 °C. This result shows a high level of thermal sensitivity of respondents with regard to T_a as 28.4 % of 748 respondents were in the comfort band of -1 to +1 within 0.6 °C gap of T_a. Conversely, in the cool season, 93.5 % of respondents voted within -1 and +1 at a range of T_a of 28.3–32.3 °C.

It is worth noting that in the cool season (refer Fig. 4a), the majority of the respondents' votes were between -1 (slightly cool) and 0 (neutral) while in warm season, votes were between 0, neutral to +3, hot. In the warm season, only 28.1 % of the respondents voted in the acceptable ranges -1 to +1 for the T_{mrt} range of 27.5–34.5 °C, while the remaining 71.8 % voted between +2 and +3 within T_{mrt} of 34.5–80.5 °C. Conversely, in the cool season, 93.4 % of 795 respondents voted between -1 and +1 at a T_{mrt} range of 23.7–71.7 °C.

In both seasons, calculated T_{mrt} was very high, with values of up to 80 °C; however, the effect of its influence on the respondents' MTSV differs in each season. Fig. 10 shows the relationship between respondents' sense of sunny/shady and T_{mrt} for the warm and cool seasons. To explore the difference, the neutral T_{mrt} was determined by Probit analysis for the warm and cool seasons. At the 50 % line, the sensation brought by 47.3 °C in cool-season is equal to 32 °C in the warm season. MTSV for respondents who spent more than one hour outdoors were used. The study reveals that respondents experience the same magnitude of T_{mrt} differently depending on the season as shown in Fig. 10.

3.2.2. Thermal sensation votes and thermal indices

Thermal sensation votes for the warm and cool seasons for both Kawe and Tandale were analysed based on ASHRAE seven point scale (Ashrae, 2004). Fig. 5 shows the relationship between MTSV and thermal indices for the warm and cool seasons, values based on 1 °C average bin. Solid and dashed lines indicate the warm and cool season respectively while dashed vertical lines indicate the maximum index temperature below which thermal sensation votes are logical. Both thermal indices showed similar trend with the highest correlation of MTSV in the warm season. At higher index temperature (> 43 °C UTCI), respondents' MTSV were not proportional to the increase of index temperature. In the warm season, the largest percentage of respondents' votes (72 %) were +2 and +3. In the cool season, 91 % of the votes ranged from -1 to +1 and only 4% were below -2 or above +2. The tough warm conditions dominating the warm season depicts the way respondents' votes are skewed toward the hot side. Ndetto and Matzarakis (2016) observed a similar trend in the warm season.

An independent *t*-test was carried out at a confidence level of 95 % to determine whether there was a statistically significant difference in respondents' votes between Kawe and Tandale. The test shows that in the cool season, there was a statistically significant difference between Kawe (M = 4.1, SD = 0.72) and Tandale (M = 3.8, SD = 1.0) conditions; t (4.4), p = 0.000. However, there was no statistically significant difference in the warm season (M = 6, SD = 1.3) for both areas. Thermal sensation votes for Kawe (close to the coast) showed that respondents experience warmer conditions than in Tandale area, which is inland. This coincides with the measurement results in Table 3, which showed Kawe areas had higher temperatures than Tandale.

Fig. 6 shows percentage of respondents feeling of warmth and thermal indices for the warm and cool seasons, at the 50 % line lies the neutral temperature. Dashed vertical lines indicate the neutral temperatures as presented in Table 4. It is apparent that in the warm season, as the index temperature increases, the percentage of respondents who feel warmer increases for all thermal indices. All thermal indices showed similar trends. However, there is a clear difference between the warm and the cool season as larger percentage of respondents feel warm in the warm season. For each graph, the dashed and dotted lines represent the cool season, and the summary of the results for the two thermal indices is found in Table 4. Statistical analysis of thermal indices presented in Table 4 shows that in the dominating warm season, UTCI performs better than SET* and PET. A chi-square test for neutral temperature in the warm season shows statistically significant relationship of respondents TSV and UTCI, X^2 (15) = 28.0; p = 0.022.

3.2.3. Thermal acceptable/comfort ranges

Thermal comfort ranges were determined by considering MTSV between –0.5 and 0.5 for all seasons while acceptable ranges were determined by the intersection of fitted curves at 20 % thermal

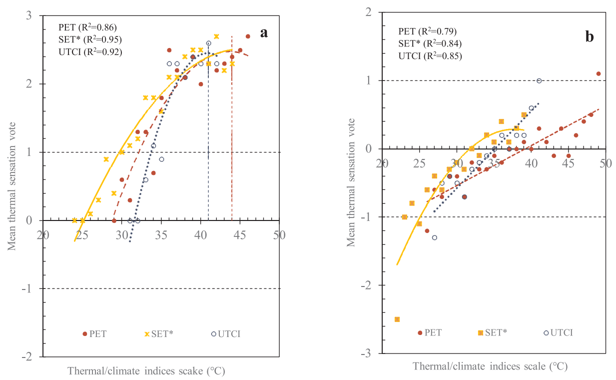

Fig. 5. The relationship between MTSV and thermal indices for the warm (a) and cool (b) seasons.

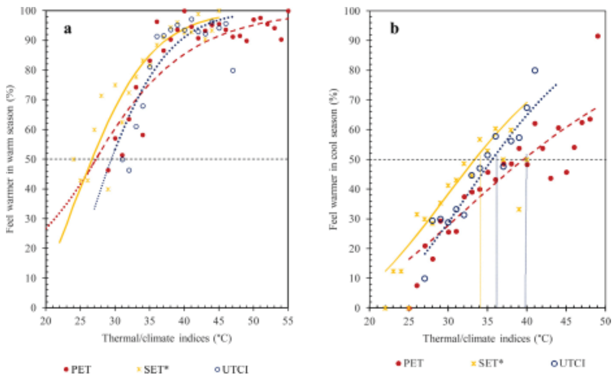

Fig. 6. The relationship between respondents' feelings of warmth and thermal indices for the warm (a) and cool (b) seasons based on the Probit method.

unacceptability. Figs. 7 and 8 present the relationship between percentage of thermal dissatisfaction and thermal indices for the warm and combined seasons for the studied informal settlements in Dar es Salaam. Fig. 7 shows the relationship between percentage of thermal unacceptability and SET*, UTCI and PET for the warm season. The size of the markers is proportional to the number of votes in each bin. Vertical dashed lines indicate the maximum index temperature where respondents' votes are logical. Dashed vertical lines marks the maximum index temperatures where TSV of respondents' have a logical pattern. At higher index temperatures, all indices show no difference on the MTSV of respondents despite an increase of temperature. At an intersection of fitted curves at the 20 % unacceptability, the upper limit of acceptability for UTCI, SET* and PET are 32.5, 27.7 and 30.2 °C, respectively. It is apparent that the majority of the respondents are on the higher percentage of thermal unacceptability. It is worth to note that the warm season is the dominant season of the year as there is no winter, and cool season lasts for a short period. Further, for the warm and combined seasons (Figs. 7 and 8) there is no lower limit because the majority of respondents voted on the warmer side of thermal sensation scale. Fig. 8 shows the relationship between the percentage of dissatisfied and thermal indices for the combined warm and cool seasons. The size of the markers is proportional to the number of respondents in each bin. At an intersection of the fitted curves at the 80 % acceptability limit (20 % unacceptability), the values of UTCI and SET* are 33.5 and 30.0 °C respectively for the combined (warm and cool) seasons.

In addition, thermal comfort ranges through regression of MTSV and thermal indices (UTCI & SET*) was determined. For the warm season, the relationship is presented by a second order polynomial function (Eqs. (3a-b). For the cool and combined seasons, the relationship is presented by both 2nd order polynomial and linear equations as shown in Eqn. 4a&b-5a&b.The following regression equations represent the relationship for the warm, cool, and combined seasons:

(a) Warm season

$$MTSV = -0.03\ UTCI^2 + 2.3\ UTCI - 44.7\ (R^2 = 0.95) \tag{3a}$$

$$MTSV = -0.0062\ SET^{*2} + 0.56\ SET^* - 10.2\ (R^2 = 0.95) \tag{3b}$$

$$MTSV = -0.011 PET^2 + 0.97\ PET - 18.7\ (R^2 = 0.86) \tag{3c}$$

(b) Cool season

$$MTSV = 0.1136\ UTCI - 3.98\ (R^2 = 0.85) \tag{4a}$$

$$MTSV = -0.008\ SET^{*2} + 0.6\ SET^* - 11.13\ (R^2 = 0.84) \tag{4b}$$

$$MTSV = 0.0587\ PET - 2.29\ (R^2 = 0.79) \tag{4c}$$

(c) Combined season

$$MTSV = 0.2041 UTCI - 6.55\ (R^2 = 0.93) \tag{5a}$$

$$MTSV = 0.1338\ SET^* - 3.69\ (R^2 = 0.97) \tag{5b}$$

3.2.4. Neutral temperature

In this study, the neutral temperature in the warm, cool and combined seasons were determined by the use of both regression (refer Section 2.5.3) and the Probit technique (Ballantyne et al., 1977). Table 4 presents a summary of the results with their statistical significance. Fig. 5 presents results for regression techniques and Fig. 6 present results for the Probit technique for both warm and cool seasons. There is a slight difference of 1 °C SET* between the methods for neutral temperature in the warm season with regression technique having results with higher values.

The neutral temperature for the warm season by the Probit analysis based on UTCI (Fig. 6a-UTCI) is a result of an extrapolated line, as the line of expected respondents did not reach 50 % (point of neutrality). Nonetheless, for the combined and cool season, the difference 1.7–3.4 °C is significant. It is worth noting that Chi-square test of independence for combined season's shows significant relationship for both thermal indices (Table 4).

3.2.5. Preferred temperature

Respondents' preferred temperature was determined by using Probit technique. Fig. 9 shows the preferred temperatures of the cool season for UTCI (26.4 °C) and SET* (21.6 °C). Preferred temperatures for the cool and combined seasons are as indicated in Table 4. It was not possible to determine the preferred temperature for the warm season as the majority of respondents' votes were on the warmer side (see Fig. 9). A huge difference was observed between the neutral temperatures and preferred temperatures in both combined and cool season for all applied indices. The preferred temperatures are lower by 9 − 12 °C than the neutral temperatures. For the combined season, preferred temperature results for UTCI showed significant relationship, X^2 (19) = 32.06; $p = 0.031$.

Table 4
Neutral and preferred index values, thermal acceptable ranges and upper thermal comfort limits (80 % thermal acceptability) for the warm, cool and combined seasons (Chi-square test were taken at 95 % confidence level, 0.05 significance level).

		Neutral index temperature value by Probit technique (Fig. 6)		Neutral index temperature value by regression (Fig. 5)	Preferred index temperature value by Probit technique (Fig. 9)		Thermal acceptable ranges by regression lines	Upper comfort limit (80 % acceptability)
Index	Seasons	$T_{neut.}$ (°C)	Chi-square test of independence	$T_{neut.}$ (°C)	$T_{pref.}$ (°C)	Chi-square test of independence	(°C)	(°C)
UTCI	Warm	29.5	X^2 (15) = 28.0; p = 0.022	31.3			30.2 – 32.5	32.5
	Cool	36.0	X^2 (13) = 8.85; p = 0.784	35.1	26.5	X^2 (13) = 13.63; p = 0.400	30.6 – 39.5	40.5
	Combined	33.8	X^2 (19) = 48.7; p = 0.000	32.1	25.0	X^2 (9) = 21.9; p = 0.090	29.7 – 34.6	33.5
SET*	Warm	26.7	X^2 (20) = 17.5; p = 0.618	25.3			23.4 – 27.4	27.7
	Cool	33.5	X^2 (17) = 9.05; p = 0.939	31.3	22.0	X^2 (17) = 6.96; p = 0.984	27.5 – 36.5	39.4
	Combined	30.9	X^2 (22) = 45.2; p = 0.002	27.6	21.6	X^2 (15) = 11.8; p = 0.697	23.9 – 31.4	30.3
PET	*Warm*	*27.5*	*X^2 (27) = 74.3; p < 0.001*	*27.7*			*25.8 – 29.8*	*30.2*
	Cool	*39.5*	*X^2 (23) = 14.5; p = 0.912*	*39.1*	*25.5*	*X^2 (23) = 18.7; p = 0.718*	*30.6 – 47.6*	*48.2*
	Combined	*33.5*	*X^2 (19) = 22.3; p = 0.270*	*30.2*	*21.5*	*X^2 (19) = 20.7; p = 0.353*	*27.4 – 33.6*	*31.8*

PET results are from Baruti and Johansson (2020) and included for comparison purposes.

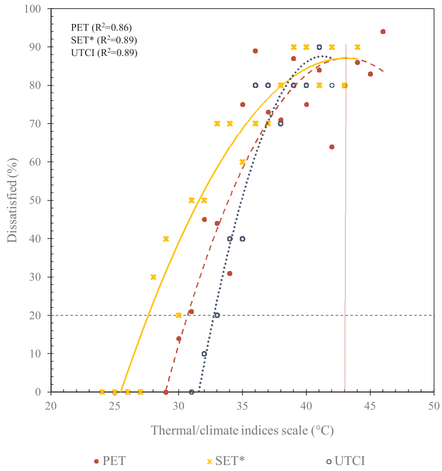

Fig. 7. The relationship between the percentage of dissatisfied and thermal indices for warm season.

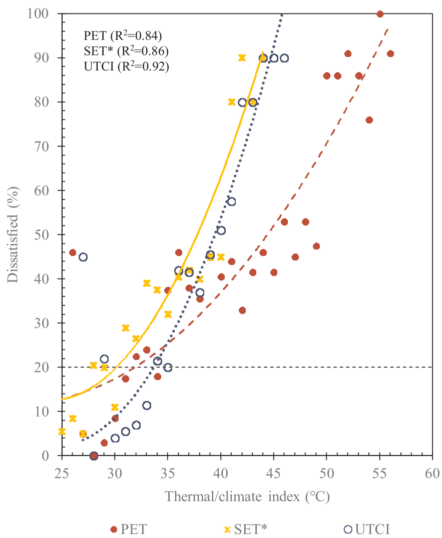

Fig. 8. The relationship between the percentage of dissatisfied and thermal indices for combined warm and cool seasons.

4. Discussion

4.1. Thermal sensation and meteorological variables

Analysis of the relationship between respondents' MTSV and meteorological variables (Fig. 3) revealed that T_a and T_{mrt} were major

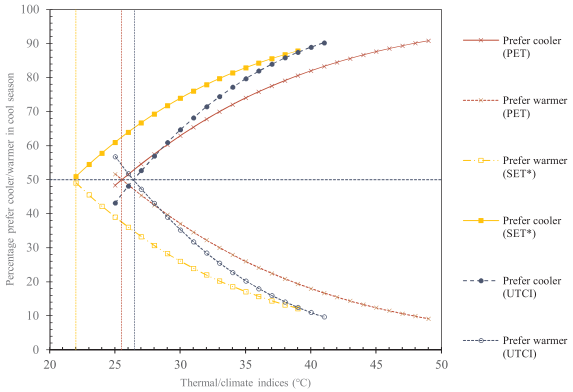

Fig. 9. The relationship between respondents' preference for warmth and thermal indices for cool season.

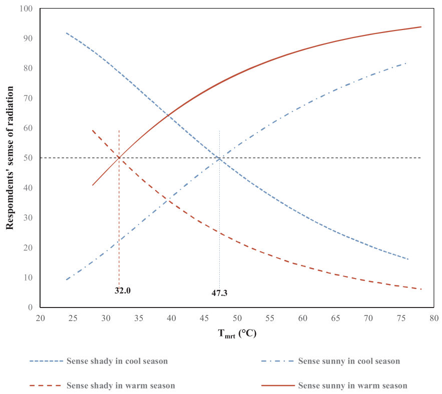

Fig. 10. Probit analysis for the relationship between respondents' sense of sunny/shady and T_{mrt} for the warm and cool season.

variables in determining thermal sensation in the dominant warm season. Air temperature strongly influences thermal sensation of the respondents in both the warm season (R^2 = 0.88) and the cool season (R^2 = 0.73). Other studies such as (Villadiego & Velay-Dabat, 2014; Zeng & Dong, 2015) have also found strong connection between T_a and thermal sensation of respondents. In addition, Villadiego and Velay-Dabat (2014) found that respondents in the warm humid tropical savannah, which is dominated by small diurnal and yearly variations of air temperature (24–32.3 °C) are highly sensitive to very small variations of air temperature. In this study, the respondents' sensitivity to the narrow range of T_a is also noted. For the warm season, the T_a range, which falls within acceptable ranges, was 0.6 °C and over 200 respondents fell within that range. Moreover, the warm season MTSV between +2 and +3 had over 500 respondents within a T_a range of 3.4 °C. Although the T_a in the cool season is higher when compared to temperate climates, the significant decrease of vapour pressure and psychological influence as regards thermal history of the tough warm season could have contributed to the respondents' MTSV.

Equally, T_{mrt} shows strong relationship with the respondents' MTSV in both the studied informal settlements. The relationship is more pronounced in the warm season (R^2 = 0.79) than in the cool season (R^2 = 0.55) as shown in Fig. 4. The warm season (October-March) is dominated by the highest amount of solar radiation (Table 2) and consequently, the study observed very high levels of T_{mrt}. Other studies (Lin, 2009; Lin, De Dear, & Hwang, 2011; Shih, Lin, Tan, & Liu, 2017) in formal urban areas also observed strong influence of solar radiation on respondents' MTSV as they were more sensible to variations in global solar radiation in both seasons. The T_{mrt} was found to determine the number of people visiting a square in the hot season (Lin, 2009), and respondents' thermal perception (Shih et al., 2017).

The respondents' response on T_{mrt} and T_a in the cool season can be explained as follows. Generally, the warm season has both high temperature and vapour pressure (Table 3). This combination is very uncomfortable as cooling of the body through evaporation is restricted (Johansson, 2016). In addition, low wind speed within the informal urban fabric areas (Table 3) as compared to general wind patterns (Table 2) worsens the thermal conditions in these areas. However, the significant decrease of vapour pressure in the cool season and a slight increase of wind speed ought to have a positive influence on the thermal condition of the respondents. Other studies (Ahmed, 2003; Ng & Cheng, 2012) on formal urban fabric areas noted that increased air movement is one of the important factors in mitigating heat stress and consequently, increases the percentage of respondents in the neutral category.

4.2. Thermal comfort and thermal indices

In the warm season, the study found a strong relationship between thermal indices used with respondents' MTSV. Both SET* and UTCI showed good correlation with MTSV. A polynomial function curve describes the relationship between mean TSV and thermal indices in warm season where the increase in MTSV decreases with increasing index values. Previous studies such as (Bröde, Kruger, Rossi, & Fiala, 2012; Fang et al., 2019; Kantor, Egerhazi, & Unger, 2012), also found strong curvilinear relationship between MTSV and thermal indices.

Further, the study observed no differences in clothing values associated with seasonal variations. The average clothing value was found to be 0.5 for each season. This is attributed to the nature of the subclimate (tropical savannah-Aw) in which annual temperature variations are small. The findings concur with other studies (Johansson et al., 2018; Makaremi, Salleh, Jaafar, & Ghaffarianhoseini, 2012; Ndetto & Matzarakis, 2016) conducted in tropical savannah where there was no significant differences in clothing values between seasons. Conversely, studies in hot-dry climate (Yahia & Johansson, 2013) and Mediterranean climate (Andrade, Alcoforado, & Oliveira, 2011) and warm humid subtropical climate (Lin, 2009) noted significant differences in clothing values between seasons. Although the average clothing insulation was the same for both seasons, there was a notable individual variation in clothing especially in the cool season. It is worth noting that SET* has a considered advantage as it incorporates actual observed values of clothing insulation and metabolic rate (Johansson et al., 2018). The advantages are vividly depicted on the correlation of SET* with MTSV. On the other hand, UTCI incorporates clothing as a function of T_a.

The warm season was dominated by higher index temperatures with the majority of MTSV falling highly around the scale of warm (+2) and hot (+3) for all thermal indices (Fig. 7) representing 72 % of the respondents' votes. For the UTCI, at temperatures beyond 43 °C, the relationship of respondents' MTSV and index temperature is not clear (Fig. 5). The same trend has been observed in other studies. For example, studies in summer of humid subtropical Guangzhou, China (Fang et al., 2019) and hot arid-Cairo, Egypt (Elnabawi, Hamza, & Dudek, 2016) found similar results when PET exceeds 40 °C. Fang et al. (2019) argue that at higher index temperatures, the actual thermal responses of respondents exceed the heat stress limits and the respondents have no choice than to choose the highest level of heat stress. This study reveals that at higher index temperatures, the respondents MTSV have no statistical significant differences despite an increase in temperature. Further, the study found that at a maximum index temperature (tangent point) of the polynomial function curve (Fig. 5a), the MTSV of respondents do not show any difference to the preceding MTSV despite an increase of index temperature. This implies that respondents at high thermal index temperatures do not recognize the increase of temperatures but judge the overall condition as stressful. In the informal urban fabric areas with limited adaptation options, this condition is referred to as psychological tolerance to the thermal environment. Thus, respondents' tolerance of tough thermal condition is psychologically grounded on the limited adaptation options they have to change the condition. Li et al. (2016) found that in the context of residential environment, adaptive options improve thermal acceptability of the residents.

4.3. Thermal acceptable/comfort range

The study found that in the warm season, there is a narrow interval of comfort ranges (2.3 − 4 °C) for all indices but specifically UTCI. The fact that a large percentage of the MTSV is concentrated to the upper indices temperatures contributes to this. Contrary to the warm season, the combined season, which used averages of TSV from both season, presents reasonable comfort ranges spanning from 4.9 to 7.5 °C for both indices. SET* was found to have acceptable ranges of 4 °C and 7.6 °C in warm and combined seasons respectively. It is evident that the biggest challenge of the dominant warm season is linked to the high and narrow comfort range, which the urbanites in the informal settlements experience.

In this study, comparison of the acceptable ranges with other studies (Huang, Zhou, Zhuo, Xu, & Jiang, 2016; Huang, Li, Xie, Niu, & Mak, 2017; Hwang & Lin, 2007; Zhou, Chen, Deng, & Mochida, 2013,) that have used UTCI and SET* in similar climates is presented in Table 5. The few studies that used UTCI in warm humid climates presented thermal acceptable ranges for the combined season only. In addition, the warm season comfort ranges based on SET* (23.4 − 27.4 °C SET*) found in this study concur with the upper limit of a similar tropical savannah study (Johansson et al., 2018) which was 25.3 °C. Nevertheless, for the combined season, the comfort ranges are still higher in this study. Theoretical implications of the findings in this study compel authors to observe the strength of the adaptation of the respondents from the informal urban fabric areas and its outdoor thermal comfort challenges. However, it is evident that the context (informal urban fabric) has a fundamental contribution to the condition as noted in a simulation study (Yahia et al., 2018) that low-rise informal urban fabric areas were more stressful urban spaces than areas with high-rise buildings.

Based on the global comparison with other studies which used similar indices (Table 5), it is apparent that urbanites in the informal urban fabric areas have narrow and higher thermal comfort range specifically in the dominant warm season with the exception of hot arid climate (Yahia & Johansson, 2013). It is worth pointing that during a pilot study, it was observed that urbanites in these informal settlements had no air-conditioning and thus the question with regard to air-conditioning was removed. A previous study (Yahia & Johansson, 2013) which was done in hot-arid climate showed that people who do not have air-conditioning have wider comfort range; however, respondents in informal settlements were found to have narrow range. Similarly, in the warm humid tropical savannah climate of Guayaqil, Equador, there was no clear difference regarding the acceptance of high values of indices temperatures between the two groups (Johansson et al., 2018). One of the general observations can be small variations of microclimatic conditions in the warm humid tropical savannah climate when compared to other climates leads to narrow thermal comfort range. In these informal settlements, factors such as very low wind speeds contribute to a narrow comfort range, as wind movement is crucial for releasing heat stress in a warm humid climate (Ahmed, 2003; Makaremi et al., 2012; Ng & Cheng, 2012). In addition, very limited adaptive options in the informal urban fabric areas also leads to narrow comfort range.

4.4. Neutral temperature

One of the notable observations is the fact that neutral temperatures are high. Despite the fact that higher neutral temperature in warm environments reveals occurrence of thermal adaptation among respondents (Hwang & Lin, 2007), it also reveals seasonal differences in respondents responses. In addition, the study observed the tendency of the cool season having higher neutral temperatures than the warm season (refer Table 4); this was also found in other studies (Johansson et al., 2018; Spagnolo & De Dear, 2003; Yahia & Johansson, 2013). The respondents' response pattern in the cool season can be linked with several factors. First, the seasonal difference of the respondents' sensation of T_{mrt} (Fig. 10), which is one of the microclimate variables with the strongest influence in determining thermal sensation is directly linked to thermal indices values. Secondly, psychological experience of the previous prolonged tough warm season contributed to the respondents' response in the cool season, which presents a huge relief in the outdoor thermal conditions. On the same note, the high sensitivity to small variations in T_a for respondents in warm humid climates can be a contributing factor to the respondents' response in the cool season since small variation of thermal index temperature can lead to a significant shift of respondents' thermal sensation votes.

4.5. Preferred temperature

This study noticed that there is a huge difference between the temperatures that respondents' desire and the temperature at which they feel neither warm nor cold. For the combined season, preferred temperatures were 7.1 and 6 °C lower than neutral temperatures for UTCI and SET* respectively. Similarly, in the cool season, the differences between preferred and neutral temperature were 8.6 and 9.3 °C for UTCI and SET* respectively. It has been observed that the difference between neutral and preferred temperature is higher for the cool season than for the combined season. The difference observed could be due to variations in experience and expectations of the respondents; this trend has also been observed in other studies in humid subtropical climate

Table 5
Comparison of thermally acceptable ranges for UTCI, SET*and PET in warm humid and some other climates.

	City, Country	Source	Thermal Indices	Acceptable index temperature ranges (°C)		
				Warm season	Combined season	Cool season
A1	**TROPICAL SAVANNA (Aw)**					
1	Dar es Salaam, Tanzania	Current study	UTCI	30.2-32.5	29.7-34.6	30.6-39.5
			SET*	23.4-27.4	23.9-31.4	27.5-36.5
2	Guayaquil, Equador	Johansson et al. 2018	SET*	Upper 25.3	Upper 29.0	Upper 30.9
			PET	Upper 25.3	Upper31.3	Upper 34.3
3	Dar es Salaam, Tanzania	Ndetto and Matzarakis (2016)	PET	23.0–31.0		
4	Dar es Salaam, Tanzania	Baruti and Johansson, (2020)	PET	25.8-29.8	27.4-33.6	
A2	**HUMID SUBTROPICAL (Cfa & Cwa)**					
5	Taichung, Taiwan	Hwang and Lin, 2007	SET*		19.7–34.7	
6	Wuhan, China	Zhou et al., (2013)	SET*		22.5-28.9	
7	Hong, Kong	Huang et al. 2017	UTCI		18.9-26.5	
8	Wuhan, China	Huang et al., 2016)	UTCI		15.1-23.3	
10	Changsha, China	Liu et al. (2016)	PET		15.0–22.0	
11	Hong Kong	Ng and Cheng, (2012)	PET	27.0–29.0		14–16
12	Chengdu, China	Zeng and Dong (2015)	PET	20.0–29.5		
13	Sun Moon Lake, Taiwan	Lin and Matzarakis, (2008)	PET		26.0–30.0	
A3	**TEMPERATE CLIMATES**					
7	Warsaw, Poland	Lindner-Cendrowska and Blazejczyk, (2018)	UTCI		9.0-26.0	
8	Athens, Greece	Pantavou et al., (2013)	UTCI		15.4-26.5	
9	Umea, Sweden	Yang et al., (2017)	UTCI	12.0-17.0		
C	**HOT-ARID CLIMATES**					
10	Damascus, Syria	Yahia and Johansson, (2013)	SET*	Upper 31.3		29.6-41.8
			PET	Upper 24.0		19.8-28.5

(Fang et al., 2019; Spagnolo & De Dear, 2003). It is common for people in warm climates to desire for lower temperatures and the urgency of expectation regarding comfortable thermal conditions increases with the difference between the neutral and preferred temperature (Hwang & Lin, 2007; Johansson et al., 2018; Spagnolo & De Dear, 2003). The huge difference found in the informal urban fabric areas indicates lack of both acceptance and adaptive options in the respondents' outdoor environment.

5. Conclusion

The main objective of this paper was to investigate the subjective thermal comfort of the urbanites in informal urban fabric areas. The authors hypothesized that the informal urban fabric areas pose a unique challenge morphologically, which could have an impact on the thermal comfort of the urbanites residing in it. There are several conclusions worth pointing out from this study:

1 Higher and narrow thermal comfort temperature ranges when compared to studies in both similar and different climates show the extent of the challenge and adaptation of the urbanites.
2 Higher differences between the neutral and preferred index temperatures complement the first conclusion that there is a huge desire for lower index temperatures for urbanites in informal urban fabric areas.
3 Respondents' thermal sensation to the microclimatic variables T_a and T_{mrt} has strong influence on respondents' thermal perception in the warm season; however, in the cool season, the pattern of TSV is strongly influenced by psychological adaptation.
4 At higher index temperatures, respondents MTSV do not differ despite an increase of the index temperature.

The fourth point brings into attention the fact that urbanites in the informal urban fabric areas have to tolerate the tough thermal conditions. In fact, within the informal urban fabric areas, there are few or none adaptation options for the urbanites, which would significantly influence the thermal conditions and even widen the thermal acceptable temperature range. This implies that further studies should investigate possible adaptation measures and their implications on the upgrading of the informal urban fabric areas. It is a known fact that there have been several measures of upgrading informal urban fabric areas worldwide; however, outdoor thermal comfort issues have not featured in those. Alternative options of widening the outdoor thermal comfort zone as suggested by e.g. (Emmanuel, 2016) can be tested for improvement of the thermal conditions.

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Declaration of Competing Interest

None.

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Appendix A

Outdoor Thermal Comfort Questionnaire

Location: ....
Date: ....
Time: ....

1. Personal information

Sex: ☐ Male ☐ Female

Age: ☐ ≤ 20 ☐ 21-35 ☐ 36-50 ☐ 51-65 ☐ 66-80 ☐ >85

☐ Live in the neighborhood ☐ Work in the neighborhood ☐ Neither of them

2. What is the reason for being in this place?

☐ On my road to home/work/school/etc ☐ See other people/Relax/Get fresh air

☐ Both ☐ Other reason ....

3. How often do you pass by this place?

☐ Daily ☐ A few times/week ☐ A few times/month ☐ Rarely ☐ First time

4. How long time have you been outdoors today?

☐ Less than one hour ☐ Between 1-2 hours ☐ Between 2-3 hours ☐ More than 3 hours

5. How did you spend the last half hour?

☐ Sitting ☐ Standing ☐ Walking ☐ Other ....

6. How do you feel in this place right now?

Cold	Cool	Slightly cool	Comfortable	Slightly warm	Warm	Hot
☐	☐	☐	☐	☐	☐	☐

7. How do you sense the climate in this place?

Temperature:	☐ Warm	☐ Neutral	☐ Cold
Sun:	☐ Sunny	☐ Neutral	☐ Shady
Humidity:	☐ Humid	☐ Neutral	☐ Dry
Wind:	☐ Windy	☐ Neutral	☐ Calm

8. How would you prefer the climate in this place?

Temperature:	☐ Warmer	☐ No change	☐ Colder
Sun:	☐ More sun	☐ No change	☐ More shade
Humidity:	☐ More humid	☐ No change	☐ Less humid
Wind:	☐ More wind	☐ No change	☐ Less wind

9. Where do you prefer to spend your free time?

☐ Indoors ☐ Outdoors ☐ Other ....

10. What type of clothing do you wear?

Shirt	*Trousers*	*Shoes*	*Traditional*	*Head*	*Other*
☐ Short sleeves	☐ Shorts/skirt	☐ Sandals	☐ Kanzu	☐ Hat	☐ ....
☐ Long sleeves	☐ Long trousers	☐ Shoes	☐ Khanga	☐ Parasol	....
☐ Singlet top			☐ Masai dress		

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Paper IV

Title

Spatial and temporal variability of microclimate and outdoor thermal comfort – focus on the informal urban fabric in warm humid Dar es Salaam

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Abstract

In developing countries, urbanization is dominated by the growth of informal settlements which represents 40-80 percent of major cities. The challenges brought up by the growth of informal urban fabric spans from social-economic to environmental. Previously, upgrading of the informal settlements focused on social-economic aspects such as provision of necessary services for the residents. Whereas the quality of outdoor thermal environment has not received much attention. This paper entails to investigate the potential of upgrading of outdoor thermal environment in the informal urban fabric of warm humid city of Dar es Salaam, Tanzania through examining the influence of incremental increase of buildings heights and addition of trees with different Leaf Area Index. The study uses simulation as a method for analysis of the warm season and calculates Physiological Equivalent Temperature (PET) as a thermal index. Results show substantial improvement of both microclimate and outdoor thermal comfort. Incremental increase of buildings heights in a street canyon to 12, 18, and 24m leads to the reduction of PET by 2.5, 2.8, and 3.8 °C respectively at 2:00 pm. Similarly, varying LAI by 2, 4, and 6 m^2/m^2 leads to reduction of mean radiant temperature to 7.9, 10.1, and 12.2 °C; while PET was reduced to 3.9, 4.7, and 5.6°C respectively at 2:00 pm. Nonetheless, upgrading of urban fabric shows marginal influence on the reduction of air temperature. Despite the fact that thermal environment improvement was noted, it was not possible to reach the comfort limits on a selected day of warm season. The findings suggest that addition of vegetation is one of the economical and most effective way for upgrading of thermal conditions in informal urban fabric areas.

Keywords

Outdoor thermal comfort; Spatial variability; Microclimate; Simulations; Informal settlements; Dar es Salaam, ENVI-met

Highlights

1. Introduction

Urban microclimate encompasses complex processes influenced by the interaction of microclimate variables (i.e., air temperature, humidity, wind speed) and the urban fabric. Urban microclimate within urban centres differs substantially from those in the surrounding natural environment as each urban fabric element - buildings, roads, parking area, factories, etc. - interact with climatic variables to create a modified microclimate. The climatic variables such as air temperature, humidity, wind speed, solar radiation, and soil temperature are very sensitive to any 3-dimensional changes in the urban settings (Sharmin *et al.,* 2017). Each urban setting creates its own microclimate and leads to spatial variability of microclimate and consequently outdoor thermal comfort.

Climate related environmental problems in tropical regions include poor dispersion of air pollutants (generally low wind speeds and lack of ventilation); high level of heat stress, which decreases productivity, reduces human comfort and increases mortality due to heat related illness; and, space cooling needs which increases energy usage, which, in turn may exacerbate climate change (Roth, 2007, Johansson, 2006). It is argued that improved urban designs that maximize thermal comfort can raise the quality of life in general, as well as helping urban dwellers cope with the episodes of hot weather and allowing year-long outdoor activities (Kalkstein and Valimont, 1986, Chen and Ng, 2012). On the same note, usage levels of urban space are more likely to increase if the outdoor environment is thermally comfortable (Nikolopoulou and Steemers, 2003).

Several studies (Ndetto and Matzarakis, 2013, Rodríguez Algeciras *et al.,* 2016, Qaid and Ossen, 2015, Johansson and Emmanuel, 2006, Zhang *et al.,* 2017, Yang and Lin, 2016) have investigated spatial variability of microclimate and outdoor thermal comfort in the formal urban fabric settings in warm humid climates. On the contrary, only a few studies (Kakon *et al.,* 2009, Yahia *et al.,* 2018, Sharmin *et al.,* 2015) have explored these issues in the informal urban fabric in warm humid climates. Baruti *et al.* (2019) noted that social, economic, and environmental challenges presented by the informal urban fabric areas have been subject of research for decades; however, outdoor thermal comfort and related issues have not. On the same note, measures for upgrading of the informal urban fabric have been explored in several studies (Wekesa *et al.,* 2011, Marais and Ntema, 2013, Huchzermeyer, 2010, Huchzermeyer, 2009, Skinner and Rodell, 1983, Del Mistro and A. Hensher, 2009, Menshawy *et al.,* 2016, Corburn and Sverdlik, 2017, Abbott, 2002) to mention a few. Discussions on the informal settlement upgrading have focused on policy issues, methods, physical and socio-economic characteristics, as well as financial aspects. The mentioned studies have shown great potential of physical improvement of the informal urban fabric; however, none of these studies have incorporated outdoor thermal comfort issues. With the current trends of urbanisation and the challenges of climate change, it is necessary to not only focus on social, economic, and environmental issues of informal settlements but also outdoor thermal comfort of its residents. In this study, the simulation modelling is used to investigate spatial variability of microclimate and thermal comfort in the informal urban fabric in the warm humid climate of Dar es Salaam. Both micrometeorological measurements and numerical modelling have been employed to study the influence of climatic variables within the urban fabric. However, the constraints associated with field measurements make numerical modelling more convenient for researchers especially in terms of investigating the effect of different design parameters (Sharmin *et al.,* 2017).

The main aim of the study is twofold: to examine the thermal conditions in the existing informal urban fabric and to investigate the effect of different measures for improvement of the thermal environment. The following measures were simulated:

(i) Addition of trees of different foliage density in the street canyon

(ii) Incremental increase of building heights on both sides of the street canyon

This study opts to utilize measures underpinned in an in-situ upgrading method with the potential of improving outdoor thermal comfort and microclimate. In view of the above-mentioned aims, the authors present a brief introduction of the city of Dar es Salaam and an overview of the growth of informal settlements.

1.1 Background

Dar es Salaam city is located along the coast of the Indian Ocean of Tanzania, in the East Africa region. The city is characterised by a monocentric form of city pattern design and planning. In Dar es Salaam, informal settlements have grown exponentially since 1960 and has resulted in a large proportion of informal urban fabric areas (Bhanjee and Zhang, 2018). The growth of informal settlements takes three distinct but overlapping forms: expansion; densification and intensification (Abebe, 2011). According to Abebe (2011), expansion can be inward, outward or independent of an existing settlement while densification refers to the infilling of the empty spaces by building structures within the realm of existing settlements. Intensification is the vertical growth of built up structures or new structures replacing the old ones (Timoth, 1995). Timoth (1995) categorises intensification as one form of the internal growth along with densification. Dar es Salaam has expanded, and still is expanding, horizontally, most of which have taken place informally due to the high demand for settlement areas caused by the population growth, including migration from other regions/cities (Peter and Yang, 2019). 2017).

The majority of informal urban settlements upgrading projects are focused on the improvement of living conditions of the urbanites. This includes improving and/or installing basic infrastructure such as water, sanitation, solid waste collection, access roads and footpaths, storm water drainage, electricity, and public lighting (Imparato and Ruster, 2003). According to (Del Mistro and A. Hensher, 2009), informal settlements can be upgraded using one of two approaches: either total redevelopment or *in situ* development. In the former, the existing informal settlement is demolished and the inhabitants relocated to suitable greenfield elsewhere, while the latter entails developing the existing informal settlement, by gradually providing to the residents, land tenure, infrastructure and, social services, such as water, sanitation and electricity (Del Mistro and A. Hensher, 2009). Total redevelopment results in disruption of the social networks and adversely affects the economic network of the residing urbanites, whereas the in-situ upgrading approach tends to minimize the extent of disruption by reducing the number of households that are relocated to another site or elsewhere on the site (Del Mistro and A. Hensher, 2009).

Figure 1: Study area locations within the city of Dar es Salaam showing Kawe along the coast and Tandale, which is inland

2. Materials and methods

2.1 Climate of Dar es Salaam

Dar es Salaam city, situated at 6°51′S and 39°18′E, is categorised by a warm humid climate (tropical savanna-Aw) according to the Köppen classification (Kottek *et al.,* 2006). The annual mean maximum temperature varies between 29 °C and 32 °C, while the annual mean minimum temperatures varies between 19 °C and 25 °C. The city experiences the highest temperatures from December to March, while the cool period with relief in thermal stress is between June and September. Relative humidity always remains high; it is about 75% most of the time, but it may vary from 55% by day to almost 100% at night. In this study, simulations were conducted for Tandale area only (see Fig. 1).

2.2 Microclimate simulations using ENVI-met 4

This study employed a numerical simulation software (ENVI-met 4.4.3)(Bruse, 2014) for analysing microclimate and outdoor thermal comfort in the studied informal settlements. ENVI-met is a simulation tool that recreates the microclimate of the outdoor environment by taking into account the interaction between climatic parameters, vegetation, surfaces, the soil and the built environment (Bruse and Fleer, 1998). It involves a sequence of mathematical calculations established by the laws of fluid dynamics and thermodynamics, which govern the atmospheric motions (Sharmin *et al.,* 2017). The ENVI-met model has a horizontal resolution from 0.5 to 10 m, and a time-step of 1-10 seconds. This high resolution is crucial for analysing pedestrian comfort and interactions between individual buildings, surfaces, and plants (Ali-Toudert and Mayer, 2007, Bruse, 1999).

The new features in ENVI-met version 4 include the simple forcing of air temperature and humidity at 2 m levels which needs input data such as maximum and minimum values of air temperature and relative humidity over a 24 h cycle (Sharmin *et al.,* 2017). The forcing also has the option to input values on an hourly basis that are collected either from weather stations or directly from on-site measurements. This new feature enables the software to account for atmospheric temporal variations and consequently represent the evolution of meteorological variables along the day (Acero and Arrizabalaga, 2016).This is one of the main improvements with respect to previous versions of ENVI-met (i.e. version 3.1). Apart from the previous 1D vegetation module (i.e. plants are modelled as vegetation columns), version 4 implements a new 3D vegetation module to describe varied shapes of plants and spatial distribution of the leaves. This version also accounts for the thermal inertia of walls and roofs (Bruse, 2014).

This study has used ENVI-met Monde in modelling the study area Tandale as shown in Fig. 2a and Fig. 2b. ENVI-met Monde is a vector-based editing system designed to bridge the gap between vector based tools such as GIS and Open Street Maps and the raster based ENVI-met (Bruse, 2015). Through its option of importing Open Street Maps Geo-data and possibilities of editing building geometry using an integrated editor, it was possible to create the ENVI-met model by transforming the complex informal urban fabric. Depending on the richness/details of the information of the Open Street Maps layers, information such as building heights, building footprints, vegetation etc. can be accurately modelled.

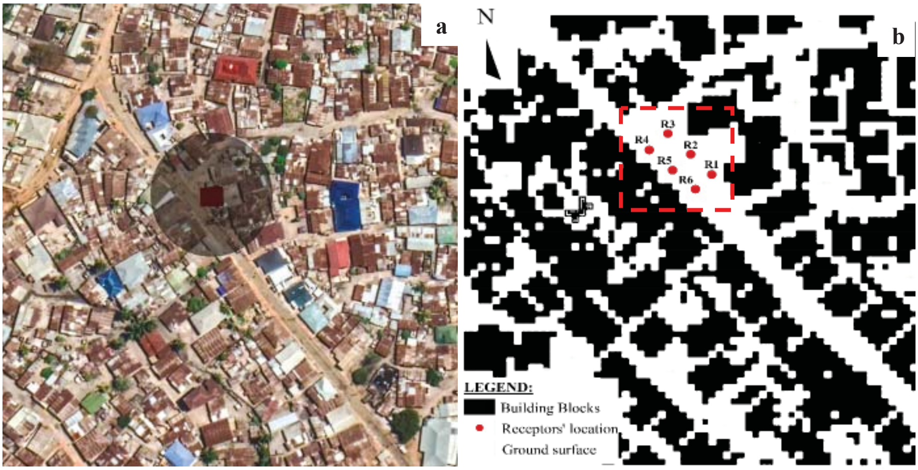

Figure 2: Study area, Tandale (a) Google Earth photo with the location of measurements (round dot) and simulated area (square highlight; (b) simulated areas as exported to ENVI-met modelling layer by the use of Open Street Map and ENVI-met Monde, R represent receptors and R1 is the receptor at the location of micrometeorological measurements

Nevertheless, in this study, the few existing trees observed in the informal urban fabric were identified by the use of Google maps.

Furthermore, this study has used ENVI-met Biomet 1.5 (Bruse, 2015) to calculate different thermal comfort indices. Despite the fact that Biomet 1.5 is capable of estimating outdoor thermal comfort using several indices such as the Physiologically Equivalent Temperature (PET) (Höppe, 1999), the Standard Effective Temperature for outdoors (SET*) (Pickup and de Dear, 2000) and the Universal Thermal Climate Index (UTCI)(Fiala et al., 2012), the study opted to present results for PET only. Moreover, PET has been widely used, including in tropical climates, thus allowing comparison with other studies globally.

2.3 Model calibration

A series of calibration tests were conducted comparing the simulated results with measured values of air temperature from Baruti et al. (2020). Air temperature has been used in several studies to validate the performance of the model (Qaid and Ossen, 2015). Figure 3 presents calibration results where the observed (measured) air temperature is compared to the predicted (simulated) air temperature for the Tandale area. The root mean square error (RMSE), which was the statistical parameter used to evaluate the performance of the model, was 0.84 °C.

Several studies (Taleghani *et al.,* 2014, Yahia and Johansson, 2014, Qaid and Ossen, 2014, Krüger *et al.,* 2011) pointed out the reliability of the ENVI-met software for simulating the outdoor thermal environment. To achieve an agreement between measured and simulated variables, adjustments were made to some of the values of the input data such as wind speed at 10m, relative humidity, and initial temperature of the atmosphere. Since the solar radiation was not measured, data from Meteonorm V.7 (Meteotest, 2014) was used. In order to adjust the solar radiation generated by ENVI-met to the Meteonorm data the solar adjustment factor was used. Table 1 shows input data used for the model for the selected month of March, which represent the warm season.

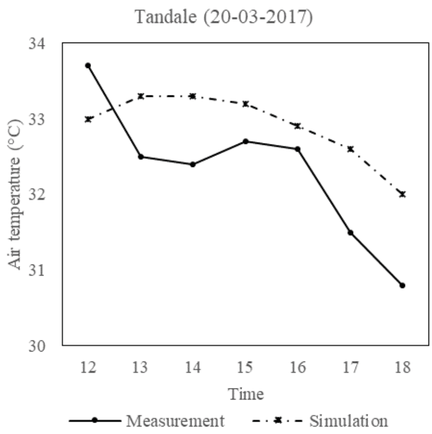

Figure 3: Comparison of measured (observed) and predicted (simulated) air temperatures for the Tandale area

Table 1: Input data for ENVI-met models for Tandale area

Category	Input data
Main canyon orientation	NW-SE
Model geometry measurements	
Model area	150m x 150m
Grid size in metres	
Dx = size of X grid	dx=2
Dy = size of Y grid	dy=2
Dz = size of Z grid	dz=2
Nr of nesting grids	10
Construction materials	
Wall material	Concrete wall (filled block)
Roof material	Iron sheets
Soil	Loamy soil
Geo reference	
Longitude	6° 47′ 36″S

Latitude	39° 14′ 39″ E
Start and duration of the model	
Date of simulation	20/03/2017
Start time	05:00
Total simulation time (h)	15
Initial meteorological conditions	
Roughness length of the measurements site	0.3
Simple forcing: Air temperature (°C)	Min 28 at 06:00; Max 35 at 12:00
Simple forcing: Relative humidity (%)	Min 60 at 06:00; Max 96 at 12:00
Wind speed at 10m height (m/s)	4
Wind direction (deg) (0° = from North, 180° = from south)	165
Solar adjustment factor*	0.95
Initial temperature of the atmosphere (K)	301
Cover of low clouds (octas)*	2
Cover of medium clouds (octas)*	2
Cover of high clouds (octas)*	2
Soil data, for all the models	**Soil humidity (%)**
Upper layer (0-20 cm)	92
Middle layer (20-50cm)	96
Deep layer (50-200cm)	96

*For the cases with vegetation the adjustment factor was 0.63 and cloud cover 0. The global solar radiation was maintained.

It is worth to point out that at the beginning of the calibration process, the study area was imported by the ENVI-met Monde with its topography. After several test simulations, the following was noted: first, simulations take longer time with the topography, and second, reading of results from the receptors required identifying the exact height of the location of the receptor and the difference in terms of height across the model was not big. In view of that, further calibration tests were conducted without topography, i.e. flat terrain.

2.4 Simulation scenarios

Simulations of Tandale were conducted based on three scenarios: incremental increase of buildings heights in both sides of the street canyon, addition of trees with varying leaf area index (LAI)[1], and combination of trees and an incremental increase of building heights of the street canyon. In this study, the base case presents the existing model of Tandale in which no upgrading measures were employed. The variables analysed were air temperature (T_a), mean radiant temperature (T_{mrt}) and thermal comfort expressed as PET. The area of investigation had the following characteristics:

(i) Single storey buildings of typical sand/cement blocks with maximum 4m height

(ii) Irregular pattern of buildings dominated by narrow footpaths (1-2 m) between buildings and limited number of roads with car access

(iii) Limited amount of vegetation that is located in few places.

[1] LAI is a dimensionless variable and is defined as one-half the total green leaf area per unit of ground surface area (Duarte et al., 2015).

Receptors were used to analyse both the existing condition and the influence of various design parameters on outdoor microclimate and thermal comfort. The six receptors were located in similar positions for the different simulation scenarios. Table 2 presents the simulation scenarios regarding increased building height. Average values of data for both microclimate and thermal comfort were analysed. In all three scenarios, the street width was increased from the base case average of 5m to 8m.

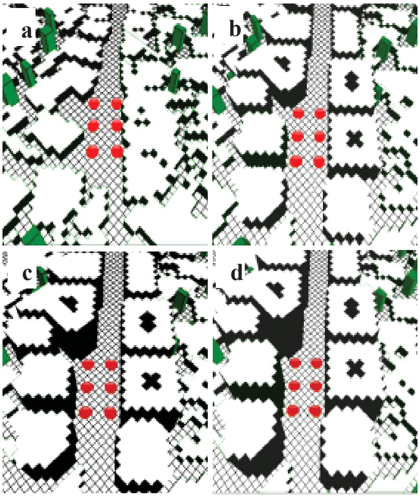

Figure 4: A 3d representation of (a) existing 4m height model (b) 12m height model (c) 18m height model, and (d) 24m height model for Tandale informal urban fabric area

Similarly, hourly meteorological data required for the calculation of PET were obtained at six points (receptors) situated as indicated in Fig.4. The location of the points was not changed in the simulation scenarios; however, the street canyon width was straightened and some building footprints modified, as part of the upgrading of the informal urban fabric, followed by gradually increasing building heights (Fig.5). The locations of the receptors represent areas where pedestrians spend most of their time. PET for each point was calculated with Rayman (Matzarakis *et al.*, 2007) based on the simulated microclimatic variables. The averaged value of PET from the six points was reported as a single PET value for each specific time and simulation scenario.

Table 2: Variation of aspect ratio and SVF for the receptors of the existing case and the different heights of the street canyon in Tandale

Receptor	Existing/Base case		Height 12m		Height 18m		Height 24m	
	H/W ratio	SVF	H/W ratio	SVF	H/W ratio	SVF	H/W ratio	SVF
R1	0.4	0.62	1.2	0.31	1.8	0.21	2.4	0.15
R2	0,33	0.72	1.2	0.35	1.8	0.24	2.4	0.18
R3	0.33	0.68	1.2	0.35	1.8	0.25	2.4	0.2
R4	0.33	0.58	1.2	0.36	1.8	0.27	2.4	0.24
R5	0.33	0.58	1.2	0.36	1.8	0.26	2.4	0.2
R6	0.4	0.59	1.2	0.34	1.8	0.25	2.4	0.19

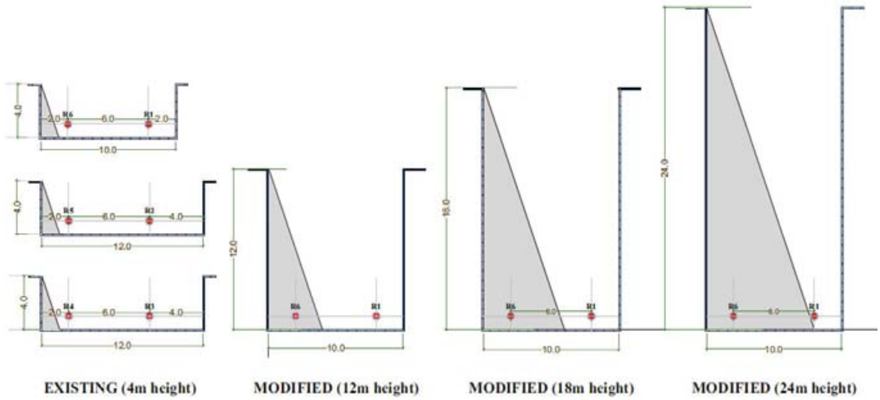

Fig. 5: A schematic cross-section of urban canyon for scenarios which involves changes of height from existing low-rise (4m) to 12m, 18m, and 24m. Red dots indicate position of receptors.

To investigate the influence of vegetation on both microclimate and outdoor thermal comfort, trees were introduced in the canyon. The types used were 10m high deciduous trees with Leaf Area Index values of two, four and six. It is worth noting that ENVI-met simulates vegetation based on Leaf Area Density (LAD)[2], thus, equation (1) (Bruse and Fleer, 1998, Morakinyo et al., 2017) which shows the relationship between LAI and LAD was used to estimate the respective LAD for the respective horizontal layer of the tree:

$$LAI = \int_0^h LAD.\Delta z \qquad (1)$$

Where:

h is the height of the tree (m), Δz is the vertical grid size (m), LAI is the leaf area index (m^2/m^2), and LAD is the leaf area density (m^2/m^3).

Table 3: Simulation scenarios, codes, upgrading measures and their objective for different study cases

Simulation scenarios	Scenario code	Measures employed within the informal urban fabric	Simulation objective for analysis
	Base case	None (4m height buildings)	Analyse existing condition
1	LAI 2 LAI 4 LAI 6	Addition of trees (LAI 2) on existing model Addition of trees (LAI 4) on existing model Addition of trees (LAI 6) on existing model	Analyse the influence of use of vegetation in the existing condition
2	H12M H18M H24M	Increase of height to 12m (4 storeys) Increase of height to 18m (6 storeys) Increase of height to 24m (8 storeys)-maximum allowable by the building regulations	Analyse the influence of building changing heights
3	H12M-LAI 6 H18M-LAI 6 H24M-LAI 6	Increase of height to 12m and trees of LAI 6 Increase of height to 18m and trees of LAI 6 Increase of height to 24m and trees of LAI 6	Analyse the influence of combining changes in building heights and LAI 6

A LAI of 6 represents a very dense tree. The influence of vegetation was analysed in two steps: introduction of vegetation in the existing model/condition for LAI of 2, 4, 6 and

[2] LAD is a parameter defined as the total one-sided leaf area (m2) per unit layer volume (m3) in each horizontal layer of the tree crown (Lalic and Mihailovic, 2004).

introduction of vegetation with an LAI of 6 while increasing the height of the buildings from 4m gradually to 12m, 18m and 24m. The detailed information on the simulations and their objectives is presented in Table 3.

It is worth to point out that all simulations which involved vegetation in the areas where receptors were located were done without clouds in order to minimize the amount of diffuse radiation. This was due to the fact that after a series of simulations, it was noted that trees were allowing large portion of diffuse radiation to pass to the ground where receptors were located and the effect of vegetation was not substantial. For that reason, clouds were removed to maximize direct radiation while maintaining the same level of global radiation for all simulations which involved vegetation. The solar adjustment factor was changed (see Table 4).

3. Results and discussion

3.1 Influence of different LAI

Addition of trees to the existing main street of the area was applied as an in-situ upgrading measure to improve microclimate and thermal comfort.

3.1.1 Temporal and spatial variations of the microclimate

Addition of trees with Leaf Area Index (LAI) of 2, 4 and 6 did not contribute to a considerable change in T_a as shown in Fig. 6a. A marginal difference (0.2°C) is observed from 12:00-15:00pm. A similar trend was observed by (Zheng *et al.*, 2018), though in their study the reduction of T_a was much higher (0.63-1.46°C). The major factors which contribute to a decreased T_a are shading from trees and evapotranspiration (Shahidan *et al.*, 2012). Studies (Bowler *et al.*, 2010, Cohen *et al.*, 2012, Papadakis *et al.*, 2001) have shown that the cooling effect of vegetation is larger on surface temperatures than on T_a. It is obvious that under a tree the reduction of radiative fluxes by canopy shading is large (Mahmoud, 2011); nevertheless, T_a around the location may not show much difference due to air turbulence within short

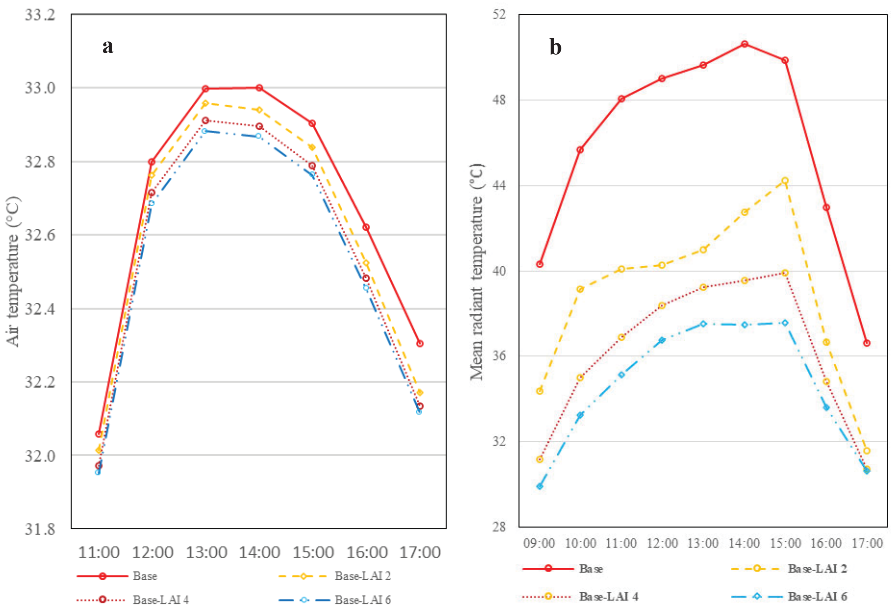

Figure 6: The influence of addition of trees with different LAI on (a) air temperature and (b) mean radiant temperature in the informal urban fabric at pedestrian height (1m)

distances (Lin *et al.,* 2017).

On the other hand, addition of vegetation showed noteworthy reduction of T_{mrt}. Application of trees with LAI 2, 4 and 6 leads to the decrease of T_{mrt} of 7.9, 10.1 and 12.2°C respectively (Fig. 6b). Fig.7 shows spatial variation of T_{mrt} at the height of 1m for the Tandale area at 2:00pm for base case and LAI of 2, 4, and 6. T_{mrt} decreases proportionally with an increase of LAI. Despite the fact that an average width of the major street was small, ranging from 4-6m, T_{mrt} was high due to the low rise building structures (Yahia *et al.,* 2018). The difference in T_{mrt} between different LAI and the base case varies with time being more pronounced around noon (11:00am–15:00pm). A similar trend was observed by (Zheng *et al.,* 2018). Trees with LAI of 6 have a potential of reaching neutral T_{mrt} which is 32°C at 2:00 pm as observed in Baruti et al., (2020). However, irrespective of the trees' species, trees have been found to have higher attenuation potential at midday when the sun is at overhead (Morakinyo *et al.,* 2017).

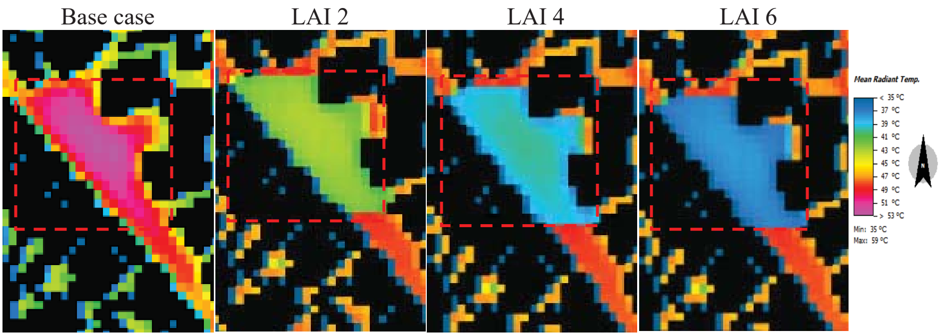

Figure 7: The influence of addition of trees with different LAI on mean radiant temperature in the informal urban fabric at pedestrian height (1m)

3.1.2 Outdoor thermal comfort

Analysis shows substantial influence of vegetation on the reduction of PET in the informal urban fabric. It was noted that addition of vegetation with LAI of 2, 4 and 6 in the existing informal urban fabric reduces the maximum PET by 3.9, 4.7 and 5.6° C respectively (Fig. 8a). This concurs with other studies, which have investigated the influence of vegetation in warm humid climates (Yahia *et al.*, 2018, Emmanuel *et al.*, 2007, Yang *et al.*, 2011, Johansson *et al.*, 2013, Tan *et al.*, 2017). For LAI of 2, 4, and 6, a reduction of PET ranging from 2.3-3.9°C, 3.8-4.7°C, and 4.5-5.6°C respectively was observed from 10:00am-4:00pm (Fig. 8b). It was shown that addition of vegetation had maximum influence on PET reduction from 11:00am-3:00pm, see Fig. 8b. The period concurs with empirical findings by (de Abreu-Harbich *et al.*, 2015). The trend is due to the effectiveness of vegetation on blocking overhead solar radiation at the midday hours as explained above for T_{mrt}. Fig.9 shows spatial distribution of PET at 2:00pm for the base case and LAI of 2, 4, and 6.

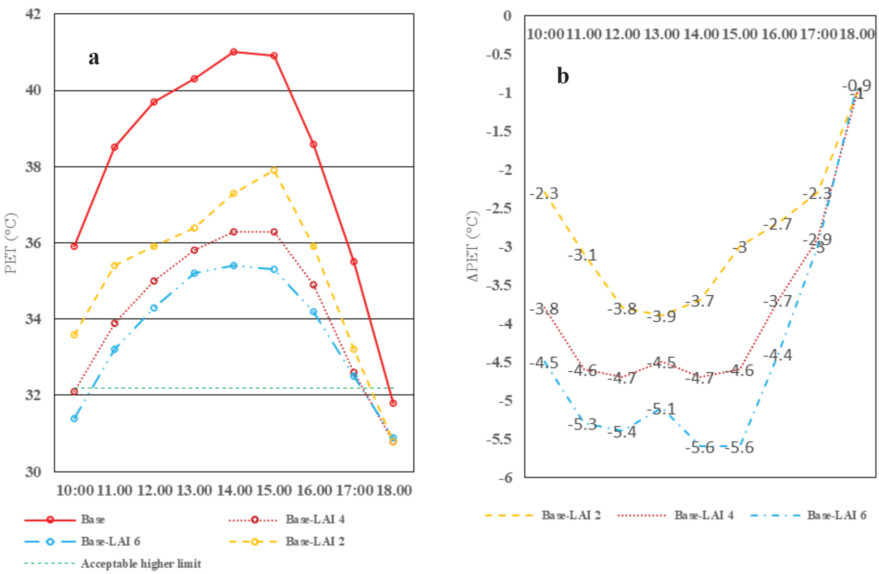

Figure 8: The influence of addition of vegetation on the outdoor thermal comfort at pedestrian height (1m) (a) and reduction of PET for different LAI values (b)

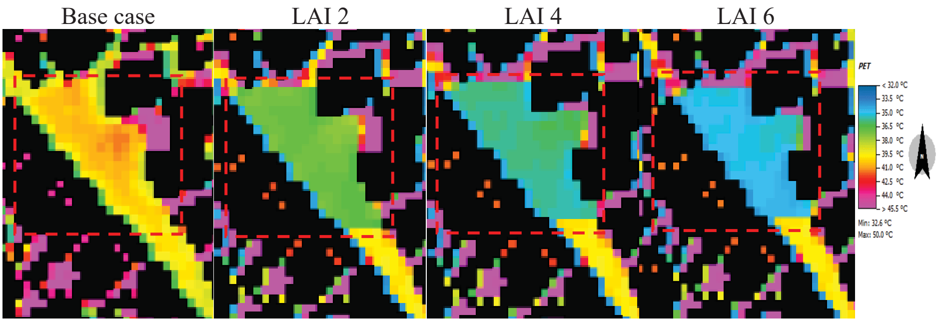

Figure 9: The influence of addition of trees on the outdoor thermal comfort at pedestrian height (1m) showing reduction of PET for different LAI

3.2 Influence of increased building heights

One of the upgrading measures for microclimate and thermal comfort within informal urban fabric areas is incremental increase of building heights. It is referred to as intensification (Timoth, 1995), and it is one among the common expansion ways in informal settlements (Abebe, 2011). In this study building heights were increased on both sides of the main street canyon.

3.2.1 Temporal and spatial variation of the microclimate

This study noted that an increase of building height shows marginal reduction of T_a (Fig. 10); a decrease of T_a by 0.25 °C was noted. This might be due to the fact that the changes have been applied in a limited area of the existing urban canyon while the large portion of the informal settlement remains the same. Another study (Andreou and Axarli, 2012) also notes a weak relationship between T_a and a changing urban geometry. This can be explained by the fact that air temperature distribution is not only affected by urban geometry but also by the combined effect of surface characteristics and air mixing rate, etc. (Santamouris, 2001). However, another study found a strong relationship between the urban fabric geometry and canyon surface temperature (Van Esch *et al.,* 2012). Other studies in warm humid climates such as (Villadiego and Velay-Dabat, 2014, Baruti *et al.,* 2020) noted the sensitivity of respondents to a small decrease in T_a; however, it is not easy to ascertain the impact of the decrease of 0.25 °C on the residents.

Studies have shown that areas with low-rise buildings have more thermally stressful urban spaces than areas with high-rise buildings (Johansson *et al.*, 2013, Yahia *et al.*, 2018). In such an environment, the low building heights make the dark coloured streets and facades exposed to the sun which increases the absorption of solar radiation and consequently increases the surface temperatures. In this study, T_{mrt} has shown variation depending on the height of the buildings within the urban canyon. This study found a substantial decrease of the average T_{mrt} with an increase in building height (Fig. 10b); for example, an increase of building heights from existing single story (4 m) to 12m high leads to a 7.2° C decrease at 2:00 pm during peak hours of the warm season. Further increase of building height to 18m and 24m shows a reduction of T_{mrt} with 9.4 and 11.2 °C respectively (Fig.10b). Similarly, other studies (Emmanuel and Johansson, 2006, Kakon *et al.*, 2009, Kakon *et al.*, 2010) in warm humid climates have shown that an increase in building height, and consequently an increase in H/W ratio, significantly reduces $T_{mrt.}$ Although the increase in building height shows significant reduction in T_{mrt}, it is difficult to reach neutral T_{mrt} which was found to be 37° C (Baruti *et al.*, 2020). This is due to the fact that an increase in building height alone cannot provide effective shade in areas close to the Equator due to high solar elevation around solar noon (Yahia *et al.*, 2018).

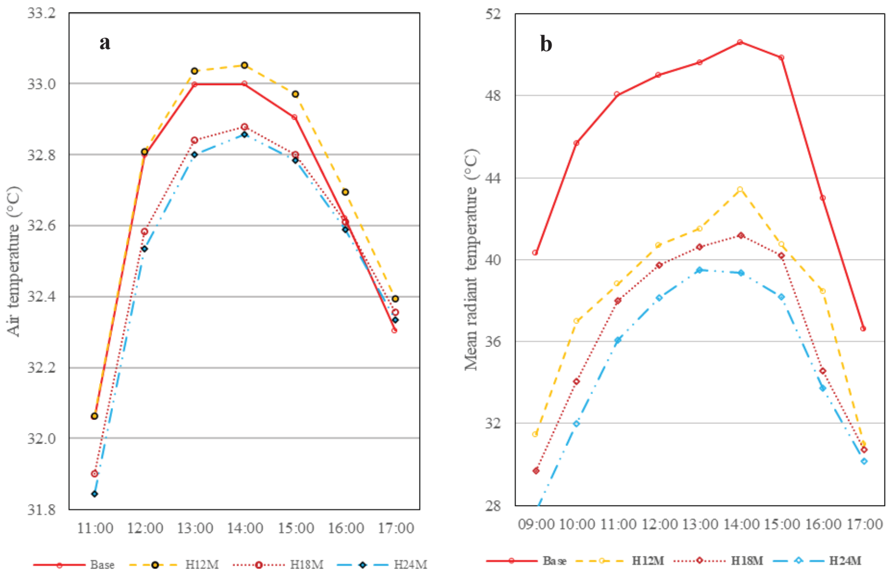

Figure 10: The influence of an increase in building height on air temperature (a) and mean radiant temperature (b) within the informal urban fabric

3.2.2 Outdoor thermal comfort

The reduced T_{mrt} due to the increase of building heights leads to a reduction of PET in spite of the decrease of wind speed. An increase of building height from single storey (4 m) to 12m reduces maximum PET at 2:00 pm from 41°C to 38.5°C (Fig. 11). Further increase of the height to 18m and 24m leads to reduction of PET by 2.8°C and 3.8°C respectively. For building heights of 12m, 18m, and 24m, a reduction of PET ranging from 2.0-3.0°C, 2.7-4.0°C, and 4.1-4.6°C respectively was observed from 10:00am-4:00pm (Fig. 11b). Increasing building heights had maximum influence on PET reduction from 10:00am-3:00pm as shown in Fig. 8b. However, the highest reduction is noted in the morning hours around 10:00am and in the late afternoon (4:00) where different building heights show a similar trend (Fig. 11b).

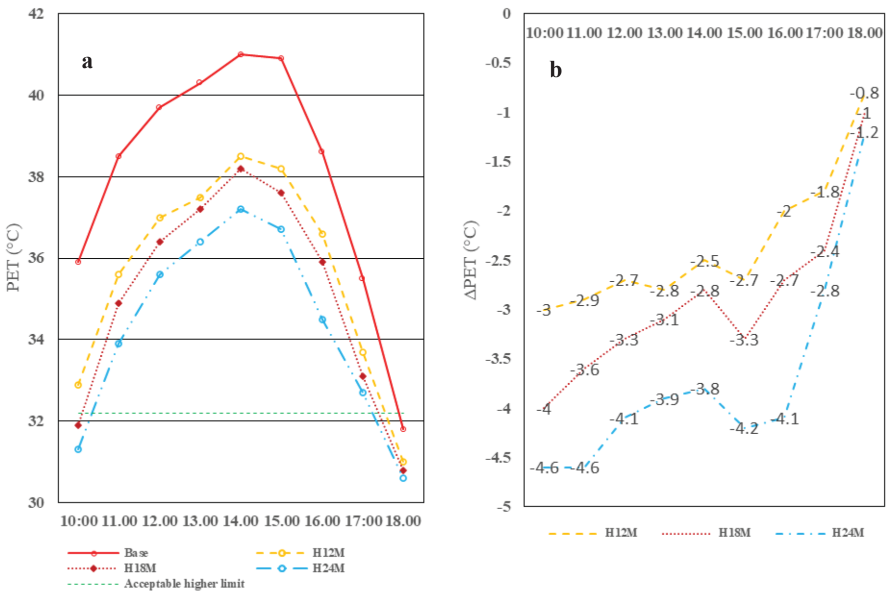

Figure 11: The influence of increase in building height on outdoor thermal comfort at pedestrian height (1m) in the informal urban fabric.+ UPPER LIMIT…

The fact that the highest reduction of PET occurs in the morning and afternoon can be explained by the low solar angle at that time. As the solar angle increases, the effectiveness of the building heights on reducing solar radiation attenuation is reduced substantially which is reflected on the PET trend from 10:00am-6:00pm (Fig. 11b).

Despite the fact that there is a noticeable reduction of PET, it is not possible to reach the comfort limits during hot days of the warm season as indicated in Fig. 11a. The dashed horizontal line indicates thermal acceptable limits during the warm season. An increase of building height to 24m in these informal settlements is 5°C PET short of the acceptable thermal limits of 32.2°C PET as shown in a previous study (Baruti *et al.,* 2020). The response of different building heights which marks the changing deepness/shallowness of the canyon is proportional to the improvement of thermal comfort by shadow-cast as noted by (Morakinyo *et al.*, 2017). Furthermore, the effectiveness of shading of buildings at 6°S latitude is lower due to the overhead position of the sun around noon. However, a normal day will have a lower PET closer to the upper comfort limit.

3.3 Influence of combining vegetation and increased building height

3.3.1 Temporal and spatial variations of the microclimate

Upgrading of the informal urban fabric through a combination of increased building heights and addition of vegetation led to a slight improvement of T_a. The maximum decrease of T_a was noted with a building height of 24m and a LAI of 6 which was 0.25°C at 2:00 pm (Fig. 12a).

Conversely, tremendous improvement in T_{mrt} was noted. A combination of the heights of

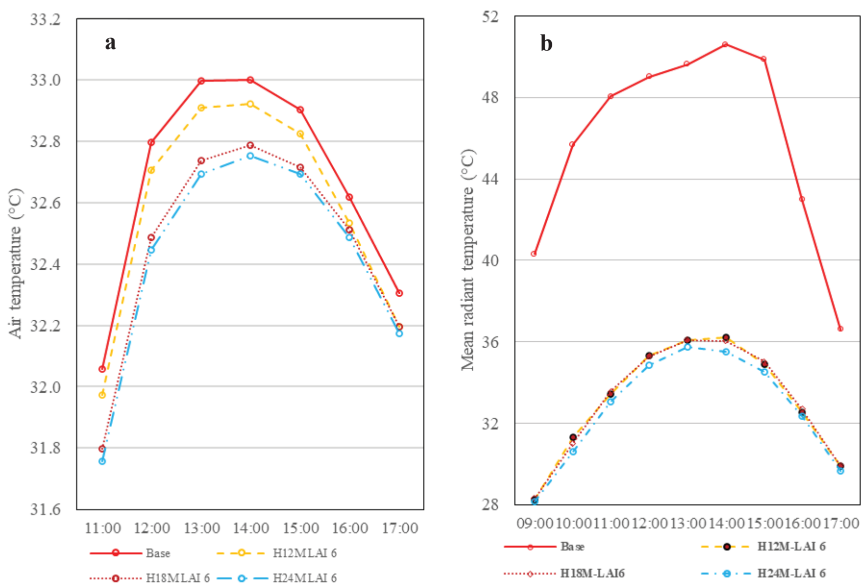

Figure 12: The influence of combination of building height and vegetation on (a) air temperature and (b) mean radiant temperature at pedestrian height (1m) in the informal urban fabric.

12m, 18m, and 24m with a LAI of 6 leads to a decrease of T_{mrt} by 12.3°C, 14.4°C and 15.1 °C respectively (Fig. 12b). In fact, it was possible to reach the neutral T_{mrt} of 37°C through these improvement measures of combined height and vegetation.

3.3.2 Outdoor thermal comfort

The study found that a combination of increased building height and adding vegetation brings about the maximum influence on outdoor thermal comfort. Though, it is not possible to reach thermally acceptable limits during the warmest month as indicated in Fig. 13a, the improvement is significant. It is worth mentioning that the study day was warmer than normal; thus, during a typical day, thermal comfort conditions will be better. Furthermore, the results show marginal differences between 12m and 18m building heights. For building heights 12m and 24m, a reduction of PET ranging from 5.0-6.2°C, and 5.2-6.4°C respectively was observed from 10:00am-4:00pm (Fig. 13b). Combining an increase of building height and adding trees had maximum reduction of PET from 10:00am-4:00pm as shown in Fig. 12b. The maximum reduction of PET of 6.4°C is found at 3:00 pm. The effect can also be seen in the spatial distribution of PET at 2:00pm (Fig.9). A comparison of Figs. 8 and 12 shows that when combining an increase of building height and addition of vegetation, it is the

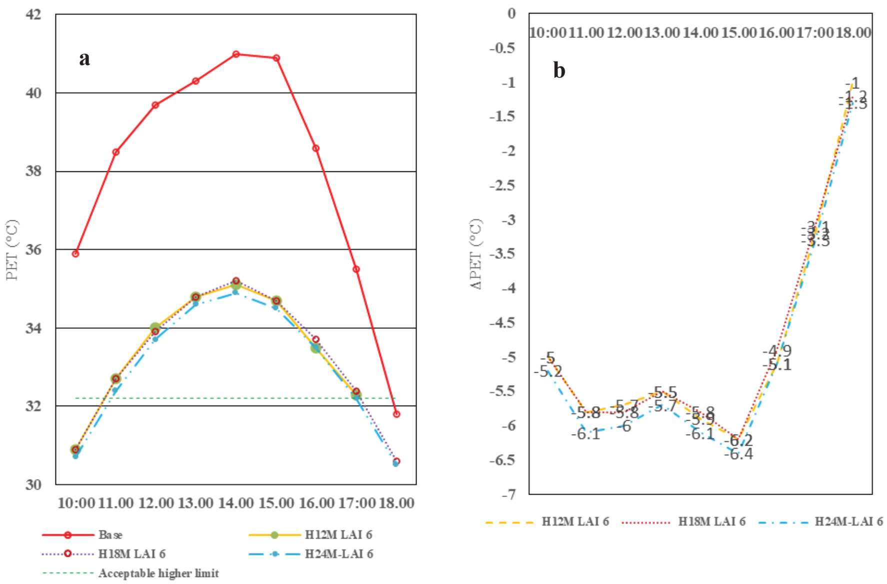

Figure 13: The influence of combination of building height and vegetation on outdoor thermal comfort in informal urban fabric

vegetation which has the highest end effect on the reduction of PET.

4.0 Conclusion

The main objective of this paper was to investigate the influence of upgrading measures on the microclimate and outdoor thermal comfort of the urbanites in informal areas. Normally informal settlements upgrading measures do not consider upgrading of the outdoor thermal environment but rather upgrading of services. An in-situ upgrading approach was considered in this study and three major upgrading measures were applied. The following notable conclusions can be highlighted:

i) the influence of increasing building heights on microclimate is more pronounced in terms of reduction of T_{mrt} . whereas changes in air temperature are insignificant;
ii) the influence of adding trees is more pronounced around midday as its capacity for solar radiation attenuation outweighs the shadows cast by the buildings at high solar elevation angles;
iii) uniform increase of building height on both sides of the canyon tends to decrease the wind speed in the urban canyon;
iv) the combination of increase of building heights and addition of trees brings about the maximum reduction of PET and T_{mrt}.

It can be argued that a cost-effective method of improving the outdoor thermal environment in the informal urban fabric is adding trees rather than increasing the building heights. Further research to investigate different tree species existing in Tanzania, their speed of growth and LAI which was beyond the scope of this study need to be conducted. Also, the need to explore how the urban landscape can contribute to informal settlements is crucial.

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Informal settlements in urban areas develop without formal planning. In these settlements, climate-related environmental challenges include poor dispersion of air pollutants, poor human thermal comfort, and high level of heat stress, which reduces productivity and leads to a potential increase of heat-related illness. This study investigated how residents of informal settlements in the city of Dar es Salaam, perceive the outdoor thermal environment. It further explored how microclimate and outdoor thermal comfort are influenced by measures such as increased building heights and addition of trees.

Solar radiation, air temperature, and air humidity were found to have a strong influence on urbanites' thermal perception. Solar radiation particularly influences thermal perception during the hottest part of the day, when the majority of residents in the outdoor environment tend to seek shade. Residents showed high sensitivity in the thermal perception to minor changes in air temperature. High air humidity and air temperatures in the wet season negatively influence residents' thermal perception, whereas a decrease in air humidity in the dry season provides relief. A significant difference in the combination of air temperature and air humidity between seasons is what defines the dry (cool) and wet (warm) seasons. Since air temperatures are moderately high in both seasons, seasonal differences in thermal perception mainly depend on the air humidity rather than temperature.

The study showed that the limited number of trees and structures such as arcades, verandas, and street canopies provide little shade to the residents in informal settlements. The lack of shading options, reported by 95% of respondents in a survey, amplifies thermal discomfort conditions. Residents in informal settlements were also found to have fairly heavy clothing regardless of the season.

During the warmest hours of the day, the majority of the urbanites perceived moderate to strong heat stress during both the wet and dry seasons.

Both an increase in tree shading capacity and incremental increase of building heights were found to considerably reduce solar radiation and improve outdoor thermal comfort in a street canyon. Increased building heights are effective in reducing the effects of solar radiation, but the effectiveness of this shade was found to be limited to the warmest hours of the day when the solar angle is high. Trees have been shown to be more efficient in reducing solar radiation because of their potential to minimise the impact of overhead sun through reduction of radiative fluxes. In reducing solar radiation, trees improve outdoor microclimate, prevent strong heat stress during warm days, and improve the wellbeing of the residents in the informal settlements.

The importance of this study is related to the need to understand residents' thermal perception of the outdoor thermal environment in informal settlements, as the outdoor thermal environment has a direct implication for residents' health and wellbeing. It can be argued that improved urban designs that optimise thermal comfort can raise the quality of life in general, as well as help urban dwellers to cope with episodes of hot weather and allowing year-long outdoor activities. If the outdoor climate is thermally comfortable, urban space use levels are more likely to increase. It is of paramount importance to equip practitioners, such as spatial planners, architects, and urban designers, with the knowledge and tools necessary for analysing microclimate and thermal comfort, and considering them in upgrades of informal settlements, urban regeneration, and urban and settlement planning. Policy makers need to be informed about the consequences of poor microclimate and outdoor thermal discomfort conditions underpinned by urban transformation. This could enable them to formulate policy guidelines that can lead to proper and appropriate urban development standards that promote thermally comfortable environments.

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