URBAN HEAT IN TROPICAL KUALA LUMPUR: MICROCLIMATE, OUTDOOR THERMAL COMFORT AND MITIGATION BY LAND-COVER MODIFICATION

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INSTITUTE FOR ADVANCED STUDIES
UNIVERSITY OF MALAYA
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DISSERTATION SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY (SCIENCE)

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URBAN HEAT IN TROPICAL KUALA LUMPUR: MICROCLIMATE, OUTDOOR THERMAL COMFORT AND MITIGATION BY LAND-COVER MODIFICATION

ABSTRACT

Urban heat island (UHI) is an urban warming phenomenon characterized by steep urban-rural temperature difference. Rapid land-use change in the urbanization process has introduced urban morphologies with impermeable surfaces and materials which causes higher heat retention in city centres. The emergence of urban hotspots is a growing concern due to the impact on the urban microclimate and human population. The comprehension of the multi-dimensional impact of UHI has become imperative to ensure good urban liveability especially in tropical cities where it is hot and humid annually. Hence, this study aims to explore the complex nexus of urban heat in terms of microclimate variations, human health implications and mitigation measures in Kuala Lumpur (KL), a rapidly developing tropical city. A study area with 500 m radius was chosen following standard microclimate monitoring procedure. Masjid Jamek (MJ), which is the selected study area from KL represents common urban morphology characterised with heterogeneous land cover and built types. This research is conducted in three phases in MJ. In Phase 1, continuous monitoring of the meteorological parameters is carried out at 2m height to identify urban microclimate variations near-surface level. In Phase 2, a cross-sectional approach is undertaken to identify the influence of urban heat on the outdoor thermal comfort (OTC) level and heat-related health implications. In Phase 3, a microclimate modelling and simulation approach is undertaken to explore urban heat mitigation measures in urban hotspots identified in the study area. Results from urban microclimate observation indicate the exposure of urban communities to distinctive hot and humid climate with high monthly air temperature ($\bar{x}$=30.23°C, SD=3.90°C), monthly relative humidity ($\bar{x}$=69.09%, SD=13.75%) and daily solar radiation (SR) ($\bar{x}$=98.21 W/m^2, SD=119.74 W/m^2). The hot-humid urban environment and predominant (43.3%) low wind activity of 0.5 to 1.5 m/s could be the reason for the thermal discomfort in the study area. Results from 1160 eligible respondents indicated more than half of the urban dwellers (n=633, 54.7%) reported thermal discomfort characterized with slight physiological heat stress ($\bar{x}$=29.45°C PET, SD=2.11°C PET). Commonly reported heat-related health symptoms include heat exhaustion (n=569, 49.2%), tiredness (n=891, 77.0%), trouble relaxing (n=509, 44.0%) and being easily annoyed (n=471, 40.7%). Through Exploratory Factor Analysis, the 38 heat-related health symptoms are clustered into eight groups. Only pain (p=0.016), anxiety (p=0.022) and somatization (p=0.041) related symptoms were found to be significantly affected by UHI. Confounding factors such as gender, age group, ethnicity and duration of outdoor exposure in a day have varying influence towards the heat-related health outcomes. The Urban Microclimate Model developed through ENVI-MET for urban microclimate modelling and simulation was found to be reliable and accurate with moderate to strong (r=0.490 to 0.951) reproducibility of actual microclimate. Urban vegetation is the most effective urban heat mitigation strategy according to simulation results. A 15% increase in grass and tree coverage in the urban hotspot can result in a reduction of daily air temperature by 0.1°C and improvement in OTC level by 0.62°C PET. In conclusion, this study provided evidence of the deterioration of urban microclimate which led to a decline in OTC level and repercussions in heat-related health symptoms in a tropical city. The findings from the current study are expected to contribute to existing sustainable town planning practices in line with the vision of transforming KL into a top-tier liveable city.

Keywords: *ENVI-MET, Microclimate, Outdoor Thermal Comfort, Physiological Equivalent Temperature, Urban Heat Island, Urban Heat Mitigation*

PULAU HABA BANDAR DI TROPIKAL KUALA LUMPUR: MIKROKLIMAT, KESELESAAN TERMA LUAR DAN MITIGASI MENGIKUT MODIFIKASI GUNATANAH

ABSTRAK

Pulau haba bandar (UHI) adalah fenomena pemanasan bandar yang dicirikan dengan perbezaan suhu bandar-luar bandar. Perubahan penggunaan tanah yang tidak terancang telah memperkenalkan morfologi bandar yang menyebabkan pengekalan haba khususnya di pusat bandar. Kemunculan kawasan panas di bandar menjadi kebimbangan kerana kesannya terhadap iklim mikro bandar dan penduduk bandar. Pemahaman kesan UHI adalah mustahak untuk memastikan kehidupan bandar yang baik terutama di bandar tropika yang panas dan lembap sepanjang tahun. Oleh itu, kajian ini bertujuan untuk meneroka perhubungan haba bandar dari segi variasi iklim mikro, implikasi kesihatan manusia dan langkah-langkah pengurangan haba bandar di Kuala Lumpur (KL), sebuah bandar tropika yang pesat membangun. Kawasan kajian dengan radius 500 m dipilih mengikuti standard prosedur pemantauan mikroklimat. Masjid Jamek (MJ), yang merupakan kawasan kajian terpilih mewakili morfologi bandar umum yang mempunyai guna tanah dan jenis bangunan yang pelbagai. Penyelidikan ini dijalankan dalam tiga fasa di MJ. Pada Fasa 1, pemantauan berterusan parameter meteorologi dilakukan pada ketinggian 2m untuk mengenal pasti variasi iklim mikro bandar dekat permukaan. Pada Fasa 2, pendekatan "cross-sectional" dilakukan untuk mengenal pasti pengaruh haba bandar terhadap tahap keselesaan terma luar (OTC) dan implikasi kesihatan yang berkaitan dengan haba. Pada Fasa 3, pendekatan pemodelan dan simulasi iklim mikro dilakukan untuk meneroka langkah-langkah pengurangan haba bandar di kawasan kajian. Hasil pemerhatian iklim mikro bandar menunjukkan pendedahan masyarakat bandar terhadap iklim panas dan lembap dengan Ta bulanan ($\bar{x}$=30.23°C, SD=3.90°C), RH bulanan ($\bar{x}$=69.09%, SD=13.75%) dan SR harian ($\bar{x}$=98.21 W/m^2, SD=119.74 W/m^2).

Persekitaran bandar yang lembap dan panas berserta aktiviti angin rendah (43.3%) 0.5 hingga 1.5 m/s boleh menjadi sebab ketidakselesaan terma di kawasan kajian. Hasil daripada 1160 responden menunjukkan bahawa lebih separuh penduduk bandar (n=633, 54.7%) melaporkan ketidakselesaan terma yang dicirikan dengan sedikit tekanan panas fisiologi ($\bar{x}$=29.45°C PET, SD=2.11°C PET). Sementara itu, gejala kesihatan berkaitan dengan haba bandar yang sering dilaporkan adalah kelesuan panas (n=569, 49.2%), keletihan (n=891, 77.0%), masalah berehat (n=509, 44.0%) dan mudah terganggu (n=471, 40.7%). Melalui Analisis Faktor Eksploratori, 38 gejala kesihatan berkaitan dengan haba dikelompokkan kepada lapan kumpulan. Hanya gejala yang berkaitan dengan kesakitan (p=0.016), kegelisahan (p=0.022) dan somatisasi (p=0.041) berkait dengan UHI secara signifikan. Faktor-faktor seperti jantina, kumpulan umur, etnik dan tempoh pendedahan di luar dalam sehari mempunyai pengaruh yang berbeza terhadap hasil kesihatan. “Urban Microclimate Model” yang dibina melalui ENVI-MET untuk pemodelan dan simulasi iklim mikro bandar didapati jitu dan tepat dengan koherensi sederhana hingga kuat (r=0.490 hingga 0.951) dengan data dari pemerhatian mikroklimat. Vegetasi bandar adalah strategi pengurangan haba bandar yang paling berkesan. Peningkatan 15% liputan rumput dan pokok di hotspot bandar boleh mengakibatkan pengurangan purata Ta sebanyak 0.1°C dan peningkatan tahap OTC sebanyak 0.62°C PET. Kesimpulannya, kajian ini membuktikan kesan fenomena UHI di bandar tropika. Kemerosotan iklim mikro bandar telah menyebabkan penurunan tahap OTC dan kesan pada gejala kesihatan. Kajian ini diharapkan dapat menyumbang kepada perancangan bandar lestari selaras dengan visi mengubah KL menjadi bandar raya bermutu tinggi.

Kata kunci: *ENVI-MET, Mikroklimat, Keselesaan Haba Luar, Suhu Setara Fisiologi, Pulau Haba Bandar, Mitigasi Pulau Haba Bandar*

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LIST OF SYMBOLS AND ABBREVIATIONS

A	:	Total study area in m^2
A_{grass}	:	Area of grass in m^2
aOR	:	Adjusted Odd Ratios
A_{shrub}	:	Area of shrub in m^2
AT	:	Apparent Temperature in °C
e	:	Margin of error
f_{cl}	:	Clothing surface area factor
G_g	:	Green Index
h_c	:	Convective heat transfer coefficient in W/m^2*K
M	:	Metabolic rate in W/m^2
OR	:	Odds Ratio
P_a	:	Water vapour partial pressure in Pascal
RH	:	Relative humidity in %
SD	:	Standard deviation
svp	:	Saturated vapour pressure in hPa
Ta	:	Air temperature in °C
t_{cl}	:	Clothing surface temperature in °C
Td	:	Dew-point temperature in °C
Tg	:	Globe temperature in °C
Tmrt	:	Mean radiant temperature in °C
Twb	:	Wet bulb temperature in °C
VP	:	Vapour pressure in hPa
W	:	Effective mechanical power in W/m^2
WD	:	Wind direction in °
WS	:	Wind speed in m/s

AC	:	Air conditioning
AR	:	Aspect ratio
AWS	:	Automated Weather Station
CFD	:	Computational Fluid Dynamic
CI	:	Confidence Interval
CPM	:	Cool Pavement Model
DOE	:	Department of Environment
MetMalaysia	:	Department of Meteorology Malaysia
DI	:	Discomfort Index
E-W	:	East–West
EFA	:	Exploratory Factor Analysis
PLANMalaysia	:	Federal Department of Town and Country Planning
GAD-7	:	General Anxiety Disorder-7
GIS	:	Geographical Information System
GKL	:	Greater Kuala Lumpur
GFM	:	Green Façade Model
GRM	:	Green Roof Model

GNI	:	Gross National Income
HI	:	Heat Index
HRI	:	Heat-Related Illnesses
IPCC	:	Intergovernmental Panel on Climate Change
KL	:	Kuala Lumpur
KLCH	:	Kuala Lumpur City Hall
LAD	:	Leaf Area Density
LAI	:	Leaf Area Index
LCZ	:	Local Climate Zone
MJ	:	Masjid Jamek
MRT	:	Mass Rapid Transport
MTCV	:	Mean Thermal Comfort Votes
MTPV	:	Mean Thermal Preference Vote
MTSV	:	Mean thermal sensation votes
MODIS	:	Moderate Resolution Imaging Spectroradiometer
NASA	:	National Aeronautics and Space Administration
NUP 1	:	National Urbanization Policies 1
NUP 2	:	National Urbanization Policies 2
N-S	:	North-South
OSM	:	Open Street Map
OTC	:	Outdoor thermal comfort
PHQ-15	:	Patient health questionnaire 15
PHQ-9	:	Patient Health Questionnaire 9
PHQ-SADS	:	Patient Health Questionnaire for Somatic, Anxiety and Depression symptoms
PET	:	Physiological Equivalent Temperature
PMV	:	Predicted Mean Vote
PPD	:	Predicted percentage dissatisfied
RO	:	Research objective
RAD	:	Root Area Density
SHES	:	Short-term Heat Exposure Symptoms
SVF	:	Sky view factor
SR	:	Solar radiation
SEA	:	South East Asia
SET	:	Standard Effective Temperature
SEB	:	Surface Energy Balance
TSV	:	Thermal sensation votes
3D	:	Three-dimensional
UTCI	:	Universal Thermal Climate Index
UHI	:	Urban Heat Island
UHII	:	Urban Heat Island Intensity
UMM	:	Urban Microclimate Model
UVM	:	Urban Vegetation Model
WBGT	:	Wet Bulb Globe Temperature

LIST OF APPENDICES

CHAPTER 1: INTRODUCTION

1.1 Background study

Urban Heat Island (UHI) phenomenon is a manifestation of poor urban planning in rapidly developing cities. The formation of UHI is driven by extensive development to support the growing population and to achieve national growth simultaneously. Studies have found evidence associating urban growth and UHI with socioeconomic indicators such as population, electricity power consumption and gross domestic product (Ibrahim, 2017; Zhang et al., 2010). As a result, UHI is prompted by the urbanization effects characterized with substantial buildings and urban structures that are built densely creating narrow street canyons; low reflective and impermeable surface materials; inadequate vegetation; high level of energy consumption as well as high concentrations of urban pollutants (Elsayed, 2012a; Nuruzzaman, 2015; Rizwan et al., 2008; Santamouris, 2015; Shaharuddin et al., 2009). UHI is also aggravated by secondary contributors such as heat generated from energy usage, transportation and other forms of anthropogenic activities (Ibrahim et al., 2014; Shahmohamadi et al., 2011).

The alteration in urban morphologies causes the deterioration of the urban environment by affecting the wind and solar access pattern which are important for heat dissipation in city centres. The higher heat retention within these urban morphologies has led to an increase in land surface temperature which influences the urban microclimate. Besides UHI, the urban warming sensation is intensified by the occurrence of global climate change, especially in tropical cities. The increased surface and air temperature across the tropical South-East Asia (SEA) region has resulted in unpredicted weather events such as heatwaves (Ibrahim et al., 2014; Othman et al., 2016), chronic water shortages (The Star Online, 2016b), flash flood (Akasah & Doraisamy, 2015; Ibrahim et al., 2012; Kondoh, 2007), torrential rain (Gasim et al., 2014) and even rare episodes of hail storms (The Star Online, 2016a).

Besides the impact on the urban environment, UHI also deteriorated the quality of life for urban communities. Urban communities, especially those that are living in the city centre are prone to higher and longer heat exposure due to the UHI phenomenon. There is a rising concern on the deterioration of outdoor thermal comfort (OTC) level and heat-related illnesses in tropical cities characterized by the year-long hot and humid climate. In particular, the health and well-being of the susceptible and vulnerable group such as the children, pregnant ladies, the elderlies and those with existing complication health conditions are at higher risk. The factors and impact associated with UHI are summarized in Figure 1.1.

Since the first observation of the UHI phenomenon in the 1810s (Roth & Chow, 2012), various studies have been conducted to identify the factors contributing to the formation of UHI. In recent years, there is a rise in scientific studies to identify UHI mitigation strategies across various climates and regions using sophisticated modelling and simulation approaches. The findings from these studies are important evidence to support the active implementations of policy and guidelines to control the impact of UHI in tropical cities.

In summary, the formation of UHI has put immense pressure on the urban environment particularly on the urban microclimate. The inclusive knowledge on the impact of UHI on the health and well-being of the urban communities in a tropical city has become imperative considering the large population and constant hot-humid environment within these regions. There is also an urgent need for an evidence-based strategy to mitigate the UHI phenomenon in a tropical city. Immediate measures need to be carried out by researchers and policymakers to ensure effective urban heat mitigation and adaptation measures to overcome the expected rise of heat stress in a tropical climate.

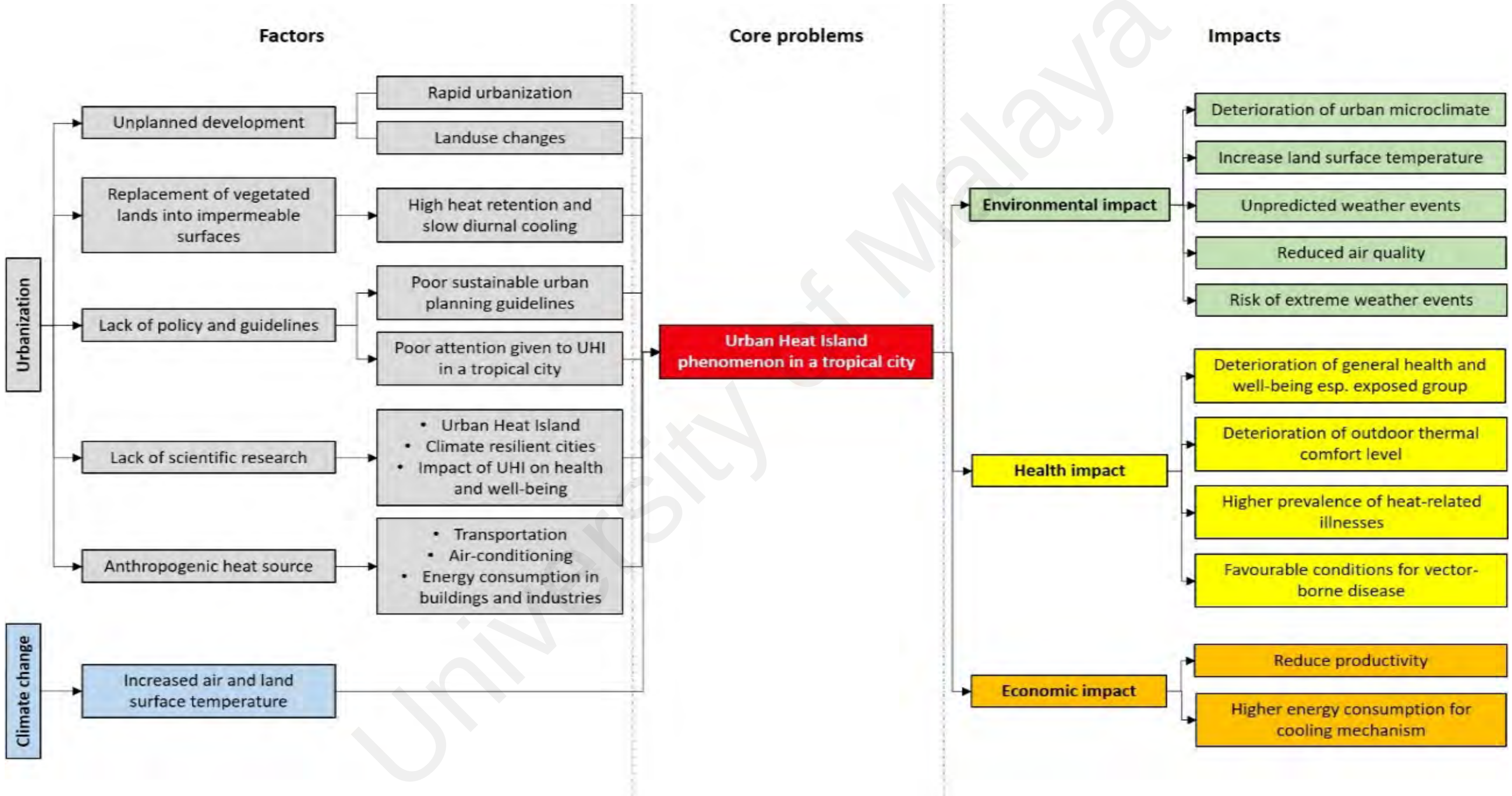


Figure 1.1: Factors and impact associated with urban heat island phenomenon

1.2 Problem statement

Kuala Lumpur (KL) is a rapidly developing tropical city which is also the capital city of Malaysia. The strategic location next to the Straits of Malacca transformed KL into a vibrant economic hub that contributes about 41% of the country's Gross Domestic Product (Ramakreshnan et al., 2019). Inevitably, the rapid development in KL has led to the formation of UHI and has been studied since 1970. In 2012, Elsayed (2012) discovered an increase of 1.5°C in UHI intensity (UHII) as compared to Sani's UHII finding of 4.0°C in 1985. Elsayed (2012) also highlighted the emergence of more heat islands while many cool islands disappeared in the city centre due to rapid land-use changes (Elsayed, 2012a). In a recent study, Ramakreshnan et al. (2019) revealed more UHI events occurring at nights within the range of 0–2.0°C (Ramakreshnan et al. 2019). Although the influence of urbanization on UHI phenomenon in KL is well documented, there are fewer studies on impacts from UHI in a tropical city because of its multifaceted complexity.

There are considerable impacts from UHI towards the health and well-being of urban communities aside from the urban microclimate. Many studies have associated the alteration of urban microclimate from UHI to an elevated temperature which affects the population's thermal comfort and human health (Acero et al., 2013; Wilby, 2007; Zhang et al., 2019). Several observational studies have shown an association between high temperatures and all-cause, cardiovascular and respiratory mortality (Buscail et al., 2012; Goggins et al., 2012; Liu et al., 2020; Michelozzi et al., 2006; O'Neill & Ebi, 2009). In hot climates, heatwaves were found to increase human heat stress and morbidity while decreases productivity (Adam-Poupart et al., 2013; Harlan et al., 2006; Kjellstrom & Hogstedt, 2009). As a consequence, medical complications such as respiratory ailments, heat exhaustion and even cardiovascular failures increases in these environments (Tan et al., 2010). Besides, increasing thermal discomfort levels in urban areas are also of major concern (Piselli et al., 2018) as they may be precursors to other heat-related illnesses. On top of the UHI phenomenon, the escalation in global climate change can be expected to cause more frequent and prolong heatwaves (Viceto et al., 2019). Unlike physical and psychological health issues due to transboundary haze, the association between UHI and health issue in a tropical city such as KL has remained unexplored (Fong et al., 2019). Besides that, there is also a clear knowledge gap concerning OTC research in tropical cities (Fong et al., 2019).

Due to the UHI phenomenon, the urban environment presents a higher threat of thermal stress than rural environments. As KL is undergoing massive urbanization, the liveability status of the urban communities is postulated at stake. Heat-related mortalities are largely preventable (O'Neill et al., 2009; Wolfe & Pauleau, 2003) but interventions for the most vulnerable populations need improvement especially now when UHI is emerging as one of the climatic threats to the poor urban population in developing countries. Therefore, strategies to mitigate UHI which subsequently improve the urban thermal environment is likely to elevate the comfort level and prevent heat-related illnesses in a tropical city (Goggins et al., 2012; Zhang et al., 2019).

In the last four decades, Malaysia has witnessed growing scientific studies to understand the UHI phenomenon as well as the development of urban heat mitigation strategies. In the early 2010s, the studies dedicated to identify urban heat mitigation strategies were only able to highlight a general context without providing much evidence of implementing such changes. For example, Elsayed (2012b) highlighted the role of land management and plant cover for lessening UHI intensity in KL and Che-Ani et al., (2009) recommended preventive action for UHI through review articles (Che-Ani et al., 2009; Elsayed, 2012b). Recently, the ENVI-MET software which is capable of urban microclimate modelling and simulation was found to be a reliable tool for UHI mitigation studies. For example, Shahidan et al. (2012a) were able to simulate an average air temperature reduction of 2.7°C by introducing higher levels of tree canopy density (Leaf area index of 9.7) coupled with “cool” materials (albedo of 0.8) in Putrajaya (Shahidan et al., 2012a). Similarly, in Putrajaya, Qaid et al. (2015) simulated the influence of aspect ratio 2–0.8 on the improvement of urban microclimate by reducing 4.7°C of air temperature (Qaid & Ossen, 2015). However, most UHI mitigation studies were focused on Putrajaya, a city built on a garden city concept. Meanwhile, studies focusing on UHI mitigation strategies in KL city centre were found to be lacking.

Acknowledging the multifaceted impact of UHI in a tropical climate, the current study presents research dedicated to understanding the impact from UHI phenomenon on the microclimate variations and implications towards human health and well-being in KL, a rapidly developing tropical city. This research also explores urban heat mitigation measures via modelling and simulation approach for the improvement of urban microclimate. The collective output from the study is expected to benefit the sustainable urban development in the long run in tandem with the vision of transforming KL to be among the top-20 most liveable cities in the world (Economic Planning Unit, 2013). This study is also dedicated to addressing goal 11 (sustainable cities and communities) and goal 13 (climate action) of the United Nation’s Sustainable Development Goals that ultimately contributes to combat the rise in global temperature by 1.5°C (Masson-Delmotte et al., 2019).

1.3 Research questions

This study aims to address the following research questions:

1. What are the impacts of urban heat island on the urban microclimate in a tropical city?
2. What are the human health implications from urban heat exposure towards the urban communities in a tropical city?
3. How reliable is the urban microclimate model to reproduce actual microclimate variation?
4. What is the best urban heat mitigation strategy to improve the urban microclimate in a rapidly developing tropical city?

1.4 Research objectives

The proposed research aims to explore the complex nexus of urban heat in terms of microclimate variations, human health implications and mitigation measures in a rapidly developing tropical city of Kuala Lumpur, Malaysia.

The specific objectives of the study are:

1. To monitor urban microclimate variations near-surface level in the study area.
2. To evaluate and associate urban heat with outdoor thermal comfort and heat-related health implications in the study area.
3. To develop, simulate and validate the three-dimensional urban microclimate model of the study area.
4. To recommend urban heat mitigation measures from four specific modes of land-cover changes for the improvements of urban microclimate parameters in the study area.

1.5 Scope of study

This study focused on one selected area representing common urban morphology setting within the city centre of KL. The study area covers a radius of 500 m following standard microclimate monitoring procedure. The study area is chosen based on the categorization of built types, land cover types and land cover properties as proposed in the local climate zone (LCZ) scheme by Stewart et al. (2012). Continuous monitoring of the urban microclimate parameters such as air temperature, relative humidity, wind speed and solar radiation is conducted daily on a 5-minutes interval for a year from January to December 2018 using automated weather station (AWS) at 2 m height from the surface level. Urban communities will be chosen randomly from the selected study area to participate in a self-reported questionnaire survey to identify the implications of urban heat towards human health. The microclimate data collected from the AWS was used for the evaluation of physiological OTC level while the findings from the questionnaire survey are used to evaluate the psychological OTC level. Other heat-related health symptoms are also identified and distinguished according to physical, psychological and psychosomatic related symptoms. Each questionnaire survey is conducted from 8:00 am to 8:00 pm to coincide with the daily diurnal variation in UHII. A site visit was conducted to collect urban geomorphological data for the development of three dimensional (3D) computational fluid dynamic (CFD) urban microclimate model in ENVI-MET software for simulation purposes. A case study scenario approach is applied to identify feasible urban heat mitigation measures for the enhancement of urban microclimate in the selected study area.

1.6 Significance of research

The significance of this research is to bridge the knowledge gap on the impacts of UHI on OTC level and human health in a tropical city. An adaptive steady-state approach is conducted to identify the physiological and psychological OTC level of urban communities which has not been done before in KL in previous studies. Five OTC indices which are Physiological Equivalent Temperature (PET), Predicted Mean Vote (PMV), Standard Effective Temperature (SET), Universal Thermal Climate Index (UTCI) and Wet-Bulb Globe Temperature (WBGT) are used to determine physiological heat stress. The psychological OTC assessment is conducted according to ISO 10551: "Ergonomics of The Thermal Environment--Assessment of The Influence of the Thermal Environment Using Subjective Judgement Scales". The association of physiological and psychological OTC is expected to reveal the true OTC level in the selected study area. A guideline to express heat stress in a tropical city which is relevant to a physiological standpoint is also proposed. This study also adopted the symptoms from a certified health screening survey questionnaire (Patient Health Questionnaire – Somatic, Anxiety and Depressive Symptoms) to identify the impact from urban heat exposure towards heat-related health symptoms among urban communities in the study area.

Due to the lack of UHI mitigation studies in KL city centre, this research explores four UHI mitigation measures in terms of urban design and greening to improve the urban microclimate in KL via 3D CFD urban microclimate model. The research is conducted in common urban morphology setting within the city centre of KL where the output from the current study can be implemented to the other zones in KL as well as other tropical cities with similar urban morphology. The urban heat mitigation measures will be implemented on the urban hotspot (area with slower heat dissipation rate as compared to adjacent areas) identified through the simulation model in ENVI-MET. The outcome from the urban microclimate model simulation is expected to identify the best urban heat mitigation measures for the improvement of urban microclimate in a rapidly developing tropical city.

The findings from the implication of urban heat exposure on OTC level and heat-related health symptoms will be crucial for intervention programs dedicated to enhancing the urban liveability status in KL. Besides that, the findings are also important to foster a climate-resilient urban community equipped with adaptation capabilities to a changing climate. The targeted approach of urban heat mitigation measures with evidence on urban microclimate improvements will be useful to various stakeholders especially policymakers and local authorities which are directly involved with urban planning. The results from the urban microclimate modelling and simulation can be used as preliminary findings to support the implementation of future urban development programs. In the long term, this research will benefit in tandem with the vision of transforming KL into a future sustainable world-class city. Concurrently, the outcome from this study is also expected to contribute in fulfilling goal 11 (sustainable cities and communities) and goal 13 (climate action) of the United Nation's Sustainable Development Goals by 2030.

1.7 Research framework

The research is centred around the UHI phenomenon in a tropical city. The theoretical framework is illustrated in Figure 1.2. Ultimately, the understanding of urban microclimate variation and human health implications which arises because of UHI with effective urban heat mitigation measures will contribute towards achieving a climate-resilient and human-centric sustainable future tropical city in KL.

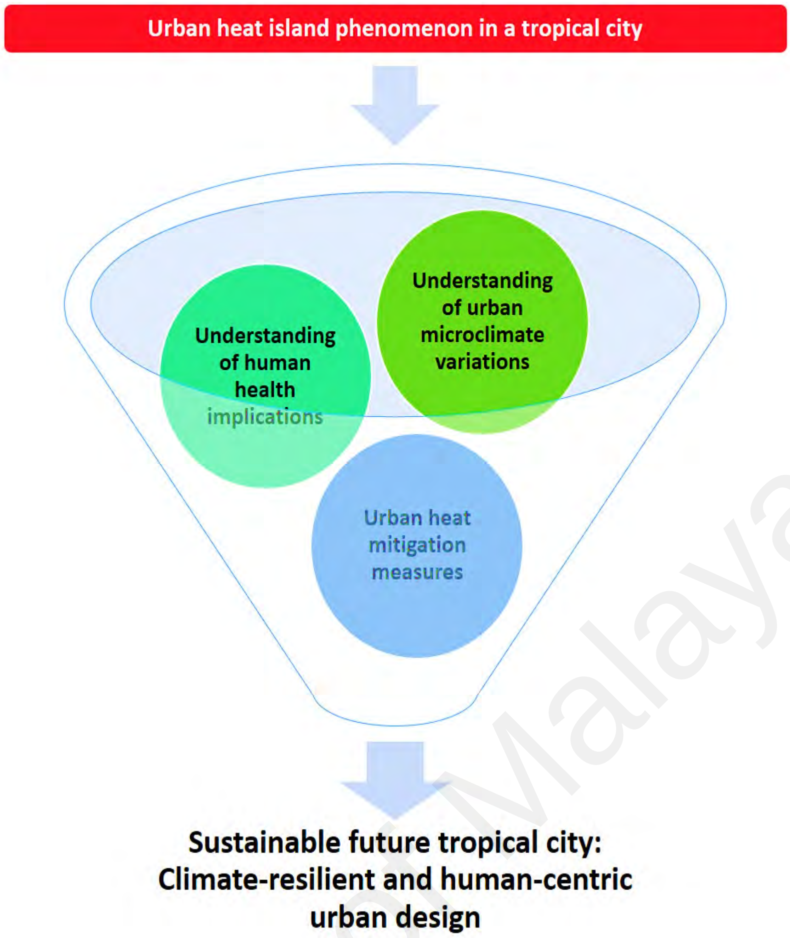


Figure 1.2: Theoretical framework of the research

The conceptual framework is presented in Figure 1.3. The main theme of the research is distinguished by the impact on the urban environment and human health implications as well as the proposed solution in terms of urban heat mitigation measures. Beneath each respective themes, the input would be the driving force of the output and outcome of the research. As illustrated in Figure 1.3, each output and outcome from the respective theme would eventually contribute to realizing a climate-resilient and human-centric urban design in a tropical city which is sustainable for the long run. The outline of the thesis is presented in the next section.

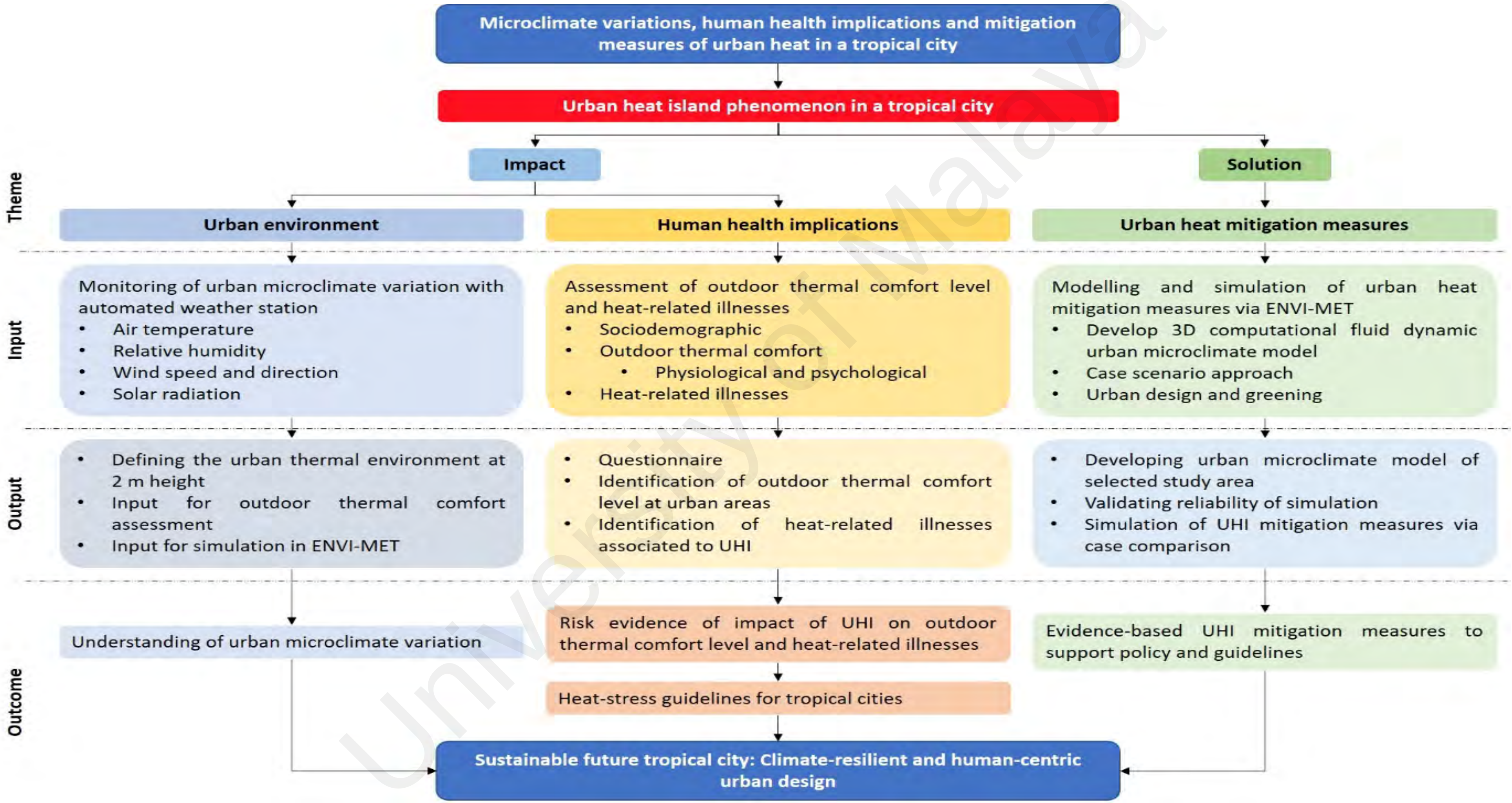


Figure 1.3: Conceptual framework

1.8 Outline of thesis

The body of this thesis consists of five chapters that cover the microclimate variations, human health implications and mitigation measures of urban heat in a rapidly developing tropical city of Kuala Lumpur, Malaysia. The chapter's outline is elaborated as follows:

i. Chapter 1 is an introduction to the research topic with a study background, problem statements, research questions, objectives, scope, the significance of the study and research framework.

ii. Chapter 2 provides a comprehensive review of literature related to the urban heat island phenomenon from a global context with a strong emphasis on the tropical climate. The literature review has been conducted focusing on the impact from UHI towards the microclimate, the implications of urban heat towards human health and well-being, as well as urban heat mitigation measures in a rapidly developing tropical city.

iii. Chapter 3 elaborates the methodologies used in the study to achieve the proposed research objectives. The methodology section focuses on procedures in carrying out urban microclimate monitoring, assessment of impact from urban heat towards outdoor thermal comfort level and heat-related health outcomes, as well as the procedure in the development of 3D CFD urban microclimate model for the simulation of urban heat mitigation measures.

iv. Chapter 4 presents the results and discussions on urban microclimate variations in a tropical city; the outdoor thermal comfort level and heat-related health outcomes from urban heat exposure; and suggested urban heat mitigation measures from the simulation of 3D CFD urban microclimate model.

v. Chapter 5 summarizes and concludes on key findings from the study; the strengths and limitations of the study; and recommendations for future urban heat-related studies in a tropical city.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The research revolves around the theme of urban heat island (UHI) phenomenon in a tropical climate with an emphasis on the impact from UHI towards the urban microclimate, health and well-being, as well as mitigation measures of urban heat via urban ecosystem management. Since the industrial revolution in 1750, anthropogenic activities such as deforestation and rapid urbanization has led to the deterioration of the natural ecosystem and the urban environment (Lindsey, 2020). The localized heating phenomenon in the urban area is driven by the replacement of vegetated lands into concrete jungles which causes high heat retention and slow diurnal cooling rate. The UHI phenomenon which is a manifestation of poor urban planning practices has led to the distinctive temperature gradient between the urban and rural areas (Ramakreshnan et al., 2018). In return, UHI has a considerable impact on the urban climate and the well-being of the communities living within. The occurrence of global climate change also worsens the impact on the urban ecosystem especially in tropical climates where it is hot and humid annually. Consequentially, various scientific studies have begun to identify urban heat mitigation measures as a preventive measure for the climatic threats towards cities and societies. However, as shown through literature review, there is lack of understanding supported with evidence in the subject matter of UHI in a tropical city especially when it relates to the impact on health and well-being as well as the mitigation measures of urban heat. Hence, the literature review has been conducted to identify the chronology of UHI studies from a global perspective and narrowed into the UHI phenomenon in a tropical city. The literature review focused on the impact from UHI towards the urban microclimate, the implications of urban heat towards human health and well-being, as well as mitigation measures to address the deleterious impact from UHI in a rapid developing tropical city.

2.2 The urban heat island phenomenon

The studies on the UHI phenomenon can be traced back near to 200 years ago. The UHI phenomenon was first investigated by Howard in 1810s, who observed that the city of London is warmer than the undeveloped rural surroundings (Roth & Chow, 2012). Figuratively, UHI is a type of urban thermal pollution which happens because of the higher ambient air temperatures in the densely built environment compared to its rural peripheries (Koegler et al., 2017; Rajagopalan et al., 2014; Roth, 2013; Rovers, 2016; Sani, 1990; Santamouris, 2015; Shahmohamadi et al., 2011; Tso, 1996). A typical UHI profile is presented in Figure 2.1.

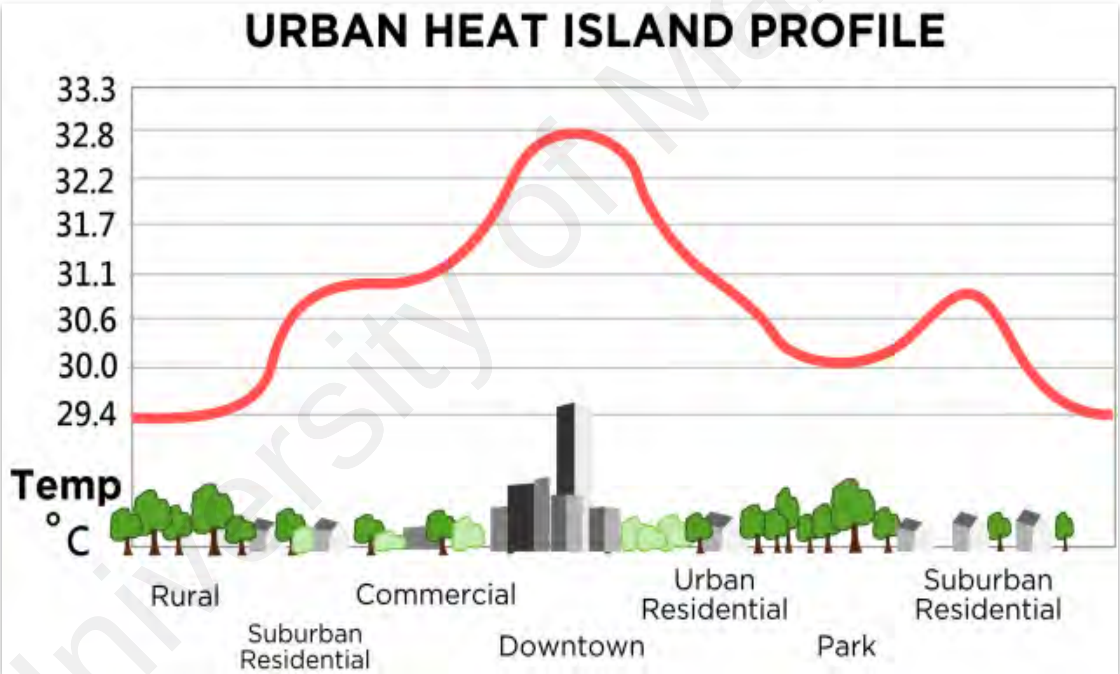


Figure 2.1: Urban heat island profile

Source: Koegler et al., 2017

2.2.1 The types of urban heat island

Although there are few types of UHI, researchers generally distinguished the UHI as either atmospheric UHI or surface UHI depending on the development, identification techniques, impacts and mitigation strategies (Benrazavi et al., 2016; Ramakreshnan et al., 2018; Roth, 2013). The comparison of atmospheric UHI and surface UHI is presented in Table 2.1. The atmospheric UHI which is divided into Canopy Layer UHI (CLUHI) and Boundary Layer UHI (BLUHI) is a result of the accumulation of warmer air in urban areas compared to the cooler air in nearby rural surroundings (Benrazavi et al., 2016). In contrast, the surface UHI is remotely sensed using thermal infrared data that allow retrieval of land surface temperatures. Factors which are associated with the UHI phenomenon is elaborated in the following section.

Table 2.1: Comparison table of atmospheric UHI and surface UHI

Characteristics	Atmospheric UHI		Surface UHI
Types	Canopy Layer UHI (CLUHI)	Boundary Layer UHI (BLUHI)	
Definition	The surface energy balance (SEB) that influences the air volume inside the canyon through sensible heat transfer from the surface into the canyon.	The extension of urban heat into the UBL through convergence of sensible heat plumes from local scale areas and the entrainment of warmer air from above the UBL	Higher air temperatures during hot and summer days in cities due to intense solar radiation on heat absorbing materials compared to ambient air temperatures in vegetated and shaded rural surroundings.
Temporal developments	Occurs during the nights with very pronounced diurnal variations and the effect during the day time is often negligible.	Occurs during both day and nights with very small magnitude that decreases linearly with the height of UBL.	Occurs during both day and nights with the highest intensity during the day time.
Spatial coverage	Local scale (1– <10km) (Limited coverage)	Meso-scale (10s km) (High coverage)	Micro-scale (1–100s m) (Limited coverage)
Measuring techniques	Stationary weather stations and mobile transverse methods.	Mainly temperature sensors mounted on airplane, helicopter, balloon and tower.	Remote sensing and often integrated with GIS applications.
Presentation methods	Temperature graphs and isotherm maps	Temperature graphs	Thermal images
Impacts	Energy and water use, thermal comfort, water use, urban air quality and urban ecology.	Local air circulation, air quality, precipitation and thunderstorm activity downwind and plant growing season.	Temperature of storm water runoff, thermal comfort and health of aquatic ecosystems.

Source: Ramakreshnan et al., (2018)

2.2.2 Factors associated to the formation of urban heat island phenomenon

The UHI phenomenon is characterized by a diurnal air temperature pattern reaching minima in the later afternoon and maxima during the night with the city centre being the most affected area (Nakano, 2015). UHI is mainly a nocturnal phenomenon attributable to urban-rural cooling differences, especially after sunset. The absorption and retention of urban heat were found to be associated to the complexity in urban morphology (Benrazavi et al., 2016; Chen et al., 2012; Gago et al., 2013; Ibrahim & Samah, 2011; Ibrahim et al., 2017; Nakano, 2015; Shahmohamadi et al., 2011; Zhao et al., 2014). The diurnal cycle is delayed in cities because urban surfaces tend to have higher volumetric heat capacity. The building materials which made the urban surfaces tend to absorb shortwave radiation and decreases the convective heat removal. Therefore, cities usually record higher temperatures especially around the roads, commercial and industrial territories (Hardin & Jensen, 2007; Nakano, 2015). On the other hand, altered urban geometry also influences the microclimate of an urban environment (Chen et al., 2012). For example, tall urban canyons in cities which reduce the sky view factor (SVF) impedes the longwave radiative exchange to the relatively cold atmosphere at night (Wong & Jusuf, 2010). High-rise building blocks in the urban area also limits the permeability of air ventilation at the pedestrian level (Ng et al., 2011). Besides that, the reduction in wind activity and evaporative cooling is also influenced by factors such as high surface roughness and decreased vegetation which is crucial to prevent heat stagnation within a city.

Meanwhile, UHI phenomenon is also aggravated by secondary contributors such as heat generated from energy usage, atmospheric pollutants from transportation and other forms of anthropogenic activities (Ibrahim et al., 2014; Shahmohamadi et al., 2011). The high amount of vehicles which emits heat via the exhaust, the cooling system, and engine also raise the air temperature in a city (Sowell, 2015). Due to the UHI phenomenon, there is also an expected increase in building energy consumption, especially on air-conditioning usage to achieve ideal thermal comfort. This worsens the urban heating phenomenon because the increased dependency on urban cooling facilities contributes to anthropogenic heat and the increase in air temperature in the urban area. The factors which are associated with the thermal modification in a city leading to a self-contained urban heat 'dome' is illustrated in Figure 2.2.

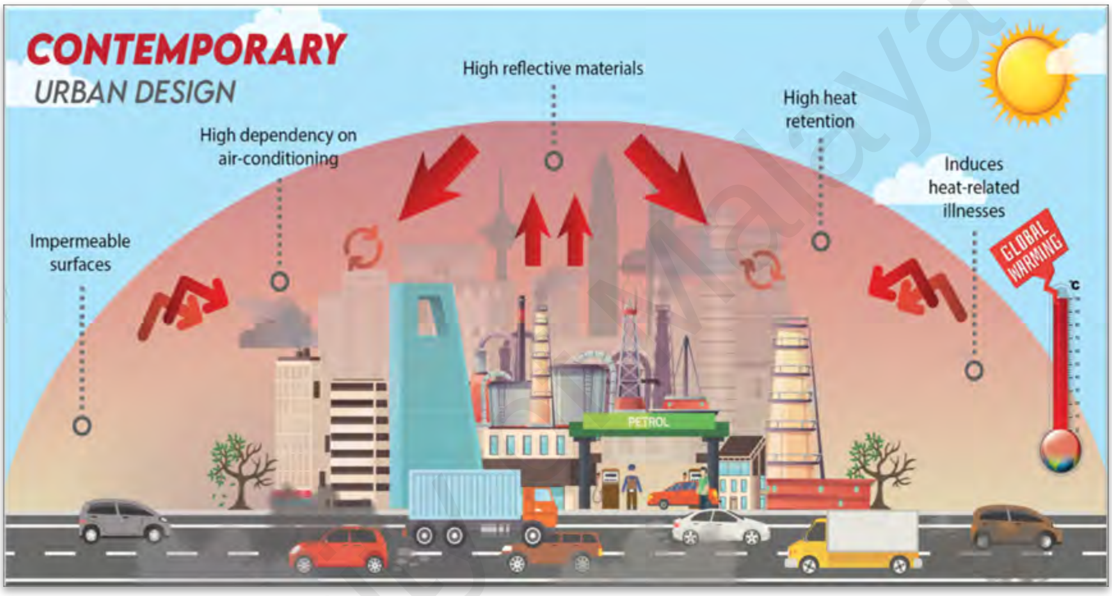


Figure 2.2: Urban heat island "dome"

The UHI phenomenon from a thermodynamic point of view is elaborated in the following section.

2.2.3 Urban heat island phenomenon from a thermodynamic perspective

The UHI phenomenon in a city is a complex energy balance for all the generated/dissipated heat from various activities within the city and the summation of incoming/outgoing solar radiation flux. The first law of thermodynamics is an iteration of principles of conservation of energy which states that the amount of energy input shall equal the energy output plus accumulation, where accumulation may be either positive or negative (Zohuri, 2018). Therefore, all energy consumed or input into the system (urban ecosystem), must be either stored or rejected to a heat sink. The dissipation of urban heat or heat energy in a city can occur in three ways of energy transfer, i.e., conduction, convection, and radiation (Oke, 1982).

Conduction is the transfer of heat from one body to another via direct surface contact while radiation is the transfer of heat in the form of electromagnetic waves (Sadık et al., 2018). An example of conductive heat transfer is the heat exchange from a building with the land surface beneath while the dissipation of long-wave radiation from urban surfaces at night is an example of radiative heat transfer. Convection is defined as heat transfer by mass motion of a fluid such as air or water when the heated fluid is caused to move away from the source of heat, carrying energy with it (Sadık et al., 2018). For example, the heat exchange which occurs when air is gusting through the buildings in a city. Among the three heat transfer pathways, convection and radiation are the significant forms of heat transfer while the amount of heat removed via conduction can be considered a very small fraction of the total dissipation of heat in a city. In compact cities, radiant energy transfer cannot occur rapidly because of the obstruction of tall buildings nearby. Therefore, the dissipation of urban heat via convection becomes important to prevent the accumulation of heat forming urban hotspots.

The wide range of energy balance systems within the UCL is mainly influenced by moisture availability, urban morphology and thermal properties of the urban surfaces (Oke, 1982). The surface energy balance is greatly influenced by moisture availability because the high specific heat capacity of water (4.18 Joule/gram °C) provides a buffering effect and allows for evaporative cooling to extend over a period time via latent heat transfer (Jim & Chen, 2009). However, impervious elements of the urban landscape such as paved roads, parking lots and buildings could only partition their radiant energy into sensible heat thus making these surfaces the sensible heat source regions for the microscale advective interaction. The urban morphology can influence the surface energy balance in several ways such as defining the surface area exposed to heat exchange processes; regulates the spatial distribution of solar radiation and precipitation inputs; influences the loss of long-wave radiation to the sky at night; and controls the turbulent flow. As a result, the radiation and energy balance regimes for simple urban morphologies could exhibit great spatial and temporal complexity. While the UHI phenomenon can be explained via thermodynamics principle, most contemporary UHI studies focused on land surface temperature as an indicator of the energy balance in an urban climate (Ibrahim, 2017). The assessment method for UHI is elaborated in the next section.

2.2.4 The assessment method of urban heat island intensity

The UHI intensity (UHII) is a principal indicator to evaluate the severity of the urbanization in an area (Rizwan et al., 2008). UHII is defined as the distinctive diurnal air temperature regimes whose differences at given times is expressed as follows:

$$\boldsymbol{UHII} = \boldsymbol{\Delta T_{urban-rural}} \qquad \text{(Eq. 1)}$$

UHII is commonly determined by comparing the mean and maximum temperatures between the urban and rural areas. In terms of study approaches, a variety of methods have been carried out to assess UHII. Most studies conducted in-situ measurements using stationary and mobile weather stations. In the meantime, there is a rise in using remotely sensed surface temperature observations as well as simulation and modelling at various scales (Aflaki et al., 2017). Besides those approaches, the surface energy balance (SEB) is another sophisticated method used to quantify the heat balance in an area (Mirzaei &

Haghighat, 2010; Rizwan et al., 2008). The land surface temperature is an important indicator of the energy balance in an urban microclimate because high temperatures modulate the energy balance which is located at the lowest layer of the atmosphere (Ibrahim, 2017; Ibrahim & Samah, 2011; Voogt & Oke, 2003). The proxy of air temperature difference could provide a much easier understanding among non-thermodynamic specialists such as urban planners, architects and policymakers. Although the UHI phenomenon is a manifestation of poor urban planning in rapidly developing countries, the UHII is affected to a certain extent by global climate change. The relationship between global climate change and UHI is elaborated in the following section.

2.2.5 The relationship of global climate change and urban heat island phenomenon

The global warming phenomena have been attributed to various anthropogenic activities such as deforestation and rapid urbanization since the beginning of the industrial revolution in 1750 (Lindsey, 2020). The Intergovernmental Panel on Climate Change (IPCC) warns that anthropogenic activities have caused the warming of about 1°C in global temperatures and suggested a high probability of a further increase by 1.5°C between 2030 to 2052 (Masson-Delmotte et al., 2019). According to the 2019's Global Risk Report, extreme weather events and failure of climate-change mitigation and adaptation measures are of major concern in terms of likelihood of happening and the resulting catastrophic impact when it happens (WEF & Collins, 2019).

Among some of the unprecedented challenges from climate change is heatwaves as they have caused mortalities that surpasses that from lightning, rain, floods, hurricanes, and tornadoes combined (Klinenberg, 2015). The escalation of global temperature is expected to cause more frequent and prolong heatwaves (Ng & Chao, 2018; Viceto et al., 2019) which may have a disastrous impact on the human population and the ecosystem. Currently, more than 50% of the world population lives in urban areas and is expected to increase to 6.4 billion by 2050 (Department of Economic and Social Affairs, 2014). The coupling effect of UHI phenomenon and global climate change impose immense threat in terms of increased surface temperature affecting the urban well-being and liveability status. The influence of UHI on the urban microclimate is further elaborated in the following section.

2.3 The impact from urban heat island on urban microclimates

The influence of UHI on the urban climate layer varies according to the spatial coverage. While the UHI phenomenon is commonly associated with horizontal temperatures, the influence of the UHI on the urban climate also extends into the overlying atmosphere. UHI is a thermal anomaly that has been observed to have horizontal, vertical and temporal dimensions (Bahi et al., 2019; Oke, 1982; Sani, 1990). It was found that UHI can influence the thermal gradient in the vertical direction with extensive cascading effects up to more than 500 m in large cities (Bahi et al., 2019; Sani, 1990).

According to the concept of urban atmosphere, the urban canopy layer (UCL) is a space bounded by the urban buildings up to their roofs whereas the urban boundary layer (UBL) extends from the rooftop or treetop level to the point where urban landscapes no longer influence the atmosphere (Oke, 1976; Ramakreshnan et al., 2018). The urban canopy layer is illustrated in Figure 2.3.

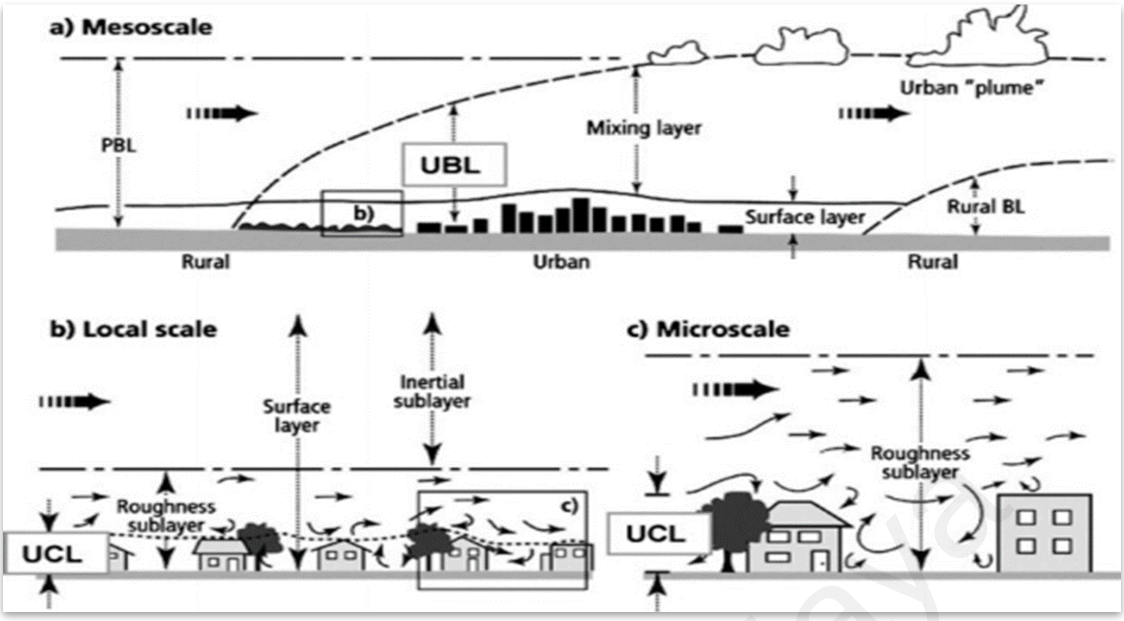


Figure 2.3: Scale and layers of urban climate
Source: Gosling et al., 2014

In urban areas, the anthropogenic and natural heat sources and sinks are located in a heterogeneous manner over a wide range of space and time scales. The exchange of energy, mass and momentum across varying urban features such as water bodies, topographic features, soil types, vegetation and land use contributes to the complexity of the city-atmosphere ecosystem. The complexity present in the UCL produces an infinite array of energy balances and therefore microclimates within the urban ecosystem. The impact of UHI on the deterioration of the urban environment is elaborated in the next section.

2.3.1 The deterioration of the urban environment

Rapid urbanization, especially in developing countries, has led to many environmental concerns (Jim, 2004). In many studies, the UHI effect is reported to be apparent under calm and weak wind conditions with the magnitudes highly influenced by diurnal and nocturnal temperature variations (Aslam et al., 2017). The elevated temperatures in city centres were found to exert great pressure towards the microclimate patterns and influence the change in precipitation pattern, air circulation, climate disasters, and deterioration of water quality and amplification of air pollutant levels (Mathew et al., 2018). Consequently, the warmer air temperature in a city triggers a series of environmental problems such as heatwaves, poor urban air quality and more frequent flood occurrence (Ibrahim, 2014; Kondoh, 2007; Yang et al., 2016; Yang et al., 2015). Apart from this, UHI also enhances urban smog by acting as a precursor for the photochemical reactions in the atmosphere (Jusuf et al., 2007). UHI has also considerable impact on building energy usage which is elaborated in the following section.

2.3.2 Impact of urban heat island on building energy usage

Besides causing the deterioration in the urban environment, escalating urban temperatures are also responsible for increasing building energy consumption for cooling (Morakinyo et al., 2019) and elevating ground-level ozone (Radhi et al., 2013; Tang et al., 2017). Due to the increasing urban heat stress, the urban population tends to stay indoors and heavily depends on air-conditioning (AC) to meet ideal thermal comfort (Golasi et al., 2018). This raises a concern because the over-dependency on AC would add to the anthropogenic heat in an urban area, triggering a never-ending loop of the urban heating phenomenon. Worse still, future projections suggested an increase in the occurrence of hot nights (daily minimum air temperature > 25°C) in a tropical city (Doan et al., 2016) hinting the dependency on AC to achieve ideal thermal comfort at night as well.

Despite a limited number of studies, previous findings revealed that increased usage of AC during summer increases electricity demands up to 2-4% for each 1°C rise in daily maximum temperature above the ambient air temperatures in warm climate regions (Rosenfeld et al., 1993). Besides that, the hike in building energy usage also indirectly contributes to global greenhouse gas emission which alters the biochemical composition in the urban atmosphere (Bhiwapurkar, 2007). Not only that but staying indoors also encourages a sedentary lifestyle that would lead to the deterioration of general health and well-being. The impacts of UHI on the health and well-being of the urban community is elaborated in the following section.

2.4 The impact of urban heat island phenomenon on human health and well-being

There is a considerable influence of UHI on human health and well-being especially when more frequent and prolong heatwaves can be expected due to the escalation in global climate change (Viceto et al., 2019) and UHI phenomenon in rapidly developing cities (Fong et al., 2019). As the UHI phenomenon becomes more prominent, the health and well-being of the urban community are potentially at risk due to the inadequate knowledge in this field. The alteration of urban microclimate which causes warmer days and nights with higher air pollution levels will influence the health and local thermal comfort especially among sensitive populations such as children, older adults and those with existing health conditions (Acero et al., 2013; Ibrahim et al., 2012; Nakano, 2015; Wang et al., 2019; Wilby, 2007). In general, the health implications from the UHI phenomenon can be distinguished according to heat-related illnesses (HRI) and outdoor thermal comfort (OTC).

2.4.1 Heat-related illnesses

The heat exchange that occurs between the human body and the environment follows the laws of thermodynamics where the core body temperature is maintained within the range of 37±1°C for the human body to function optimally (Epstein & Moran, 2006). The thermoregulatory capabilities of the human body to maintain body core temperature is important to avoid potentially hazardous health implications such as heat stroke (Kurazumi et al., 2016) and other HRI.

Several observational studies conducted globally have shown an association between high temperatures and all-cause, cardiovascular and respiratory mortality (Buscail et al., 2012; Michelozzi et al., 2006; O'Neill & Ebi, 2009). In hot climates, heatwaves were found to increase human heat stress and morbidity while decreases productivity (Adam-Poupart et al., 2013; Harlan et al., 2006; Kjellstrom & Hogstedt, 2009). On top of that, the heat stress is further intensified during the summer period (Li et al., 2018; Ward et al., 2016). As a consequence, medical complications such as respiratory ailments, heat exhaustion and even cardiovascular failures increases in these environments (Tan et al., 2010). Heat-related deaths are largely preventable (O'Neill et al., 2009; Wolfe & Pauleau, 2003) but interventions for the most vulnerable populations needs improvement especially now when UHI is emerging as one of the climatic threats to the poor urban population in developing countries. Not only that, but further health implications may also arise as urban warmth provides a favourable environment for many vector-borne diseases (Araujo et al., 2015). Besides HRI, the impact of the urban thermal environment towards the well-being of urban communities in terms of OTC has become a growing research interest in various climate. The deterioration of OTC level in an urban area is elaborated in the next section.

2.4.2 The deterioration of outdoor thermal comfort level as a consequence of urban heat island phenomenon

The declining OTC levels are one of the direct impacts from UHI phenomenon that should be of public concern (Hanipah et al., 2016; Morris, 2016; Piselli et al., 2018; Qaid et al., 2016). Due to the UHI effect, the urban environment presents a higher threat of thermal stress than the rural environment which led to the deterioration of liveability status in a city. By definition, liveability is an indication on the quality of life, the standard of living or general well-being of the population in a confined area though it may be subjective from one person to another (Okulicz-Kozaryn, 2013). A constant rise in temperature within the urban areas will lead to the aggravation of heatwaves and thermal discomfort (Ng et.al, 2012).

2.4.2.1 The concept of outdoor thermal comfort

By definition, thermal comfort is a subjective evaluation that is defined as the condition of mind that expresses satisfaction with the thermal environment (ANSI/ASHRAE 55, 2013). Thermal comfort at the urban outdoors or OTC refers to the comfort level of an individual with regards to the thermal environment at an exposed outdoor environment (Fong et al., 2019). The determination of OTC is complex because of the multifactorial interactions between the individual and the constantly varying environment. On an individual level, the thermal comfort is influenced by the physiological response of the body and the perception of the mind (psychological) towards the immediate thermal environment. Table 2.2 is a comparison table of physiological and psychological OTC.

Table 2.2: **Comparison table of physiological and psychological outdoor thermal comfort**

Physiological OTC	Difference	Psychological OTC
An indicator of how the body response to heat	**Concept**	An indicator of how the mind perceive heat
Metabolic rate, sweating rate, heartbeat or pulse, other physiological response and thermal comfort indices	**Predictors**	Difficult to predict as it is perception or opinion based
Physical variables (meteorological) that defines the thermal environment	**Influenced by**	Physical variables, surrounding aesthetics, personal expectation, behaviour and other adaptation response
Objective / Experimental measurements	**Assessment approach**	Subjective survey

An overall understanding of the interaction between the environment and the occupants will ensure achievement of suitable thermal comfort in any given thermal environment. Thermal comfort can be evaluated using various approaches depending on the thermal environment, the levels of assessments and their influencing factors (Chen & Ng, 2012). The level of assessment in OTC research is elaborated in the next section.

2.4.2.2 The level of assessment in outdoor thermal comfort research

In general, OTC assessments can be classified into four levels of assessment, i.e., physical, physiological, psychological and social behaviours. The general framework for OTC assessment is presented in Figure 2.4.

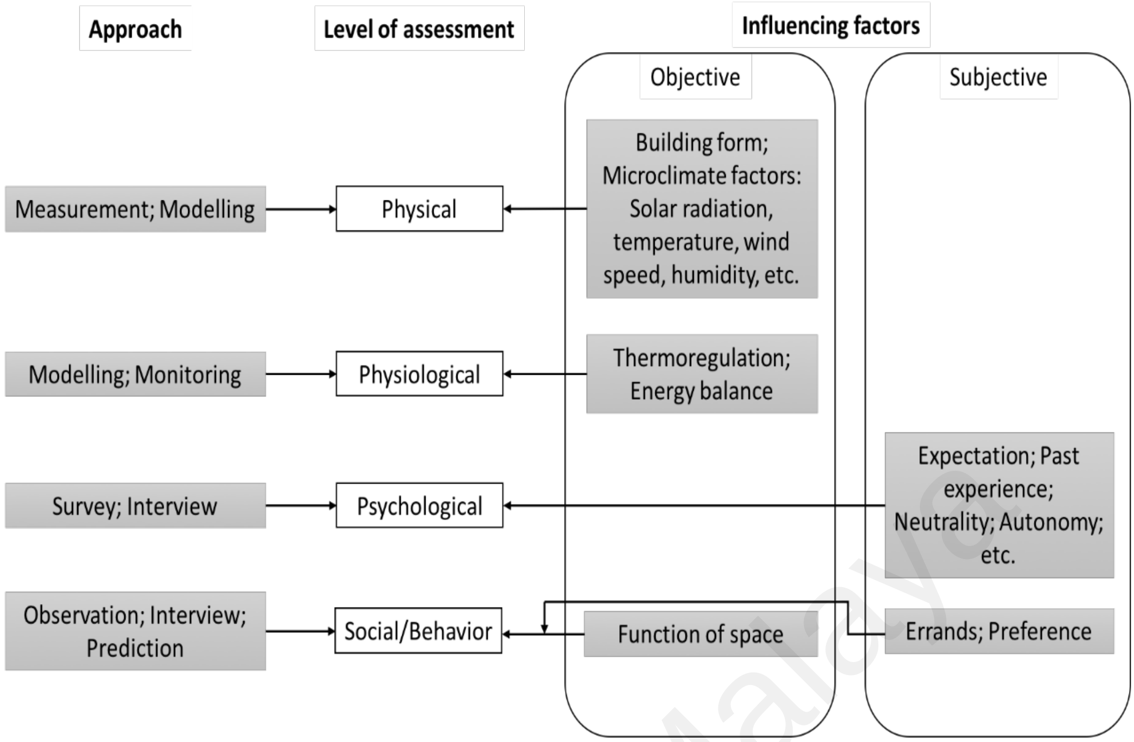


Figure 2.4: A general framework for outdoor thermal comfort assessment

Source: Chen & Ng (2012)

(a) ***Physical level***

The physical level considers the interaction of the human body with the surrounding environment which is assessed through in-situ ground measurements or modelling of microclimate parameters such as air temperature, relative humidity, wind speed, and solar radiation.

(b) ***Physiological level***

The physiological level of assessment is the study of thermoregulatory responses of the human body towards the thermal environment. Usually, physiological assessment is conducted by monitoring human physiological processes (skin temperature, metabolic rate, etc.) or modelling via thermal comfort indices. A plethora of studies has been conducted to evaluate and rate thermal stress via models and indices (Blazejczyk et al., 2012). Although these indices provide an accurate estimation of human thermal sensation by relying on the principles of human thermal exchange or the human response to various environmental factors, these indices have been criticized for disregarding numerous subjective, social, and cultural dimensions.

(c) ***Psychological level***

In contrast, the psychological level of assessment considers the feeling of the person in terms of comfort, sensation, acceptance and preference towards the thermal environment. Commonly, psychological assessment is done using questionnaire surveys and interviews. The psychological responses cannot be predicted through physical and physiological assessment alone but it is common to correlate both physical and physiological responses to psychological responses in the previous studies (Parson, 2003).

(d) ***Social behaviour***

Lastly, the level of assessment in terms of social behaviour comprises of both objective and subjective measures which are assessed through observations and interviews. Unlike the assessment of physical, physiological and psychological level which is individually subjective, social behaviour studies require a large scale of study sample as it defines the thermal environment or thermal comfort acceptance as a norm of the society.

2.4.2.3 The assessment approach of outdoor thermal comfort research

In terms of approaches for the determination of thermal comfort, there are two different approaches which are known as the steady-state and non-steady-state approach (Djongyang et al., 2010). The steady-state approach is based on a heat exchange mechanism assuming that a person's exposure to an ambient climatic environment enables a person to reach thermal equilibrium by habituation (ASHRAE, 2016; VDI, 1998). An example of this approach is the heat balance equation model by Fanger (1970) which considers both environmental (air temperature, mean radiant temperature, humidity, and wind speed) and personal factors (human activity and clothing level) while determining thermal comfort level (Fanger, 1970). On the other hand, the non-steady-state approach which is mainly based on laboratory experiment under controlled conditions is commonly insufficient to express thermal comfort conditions at outdoors as it fails to account for the dynamic aspects of human thermal adaptation (Chen & Ng, 2012).

Since both steady-state and non-steady-state approach has their pros and cons, numerous thermal comfort researchers recommended an adaptive approach where field measurements are conducted along with laboratory studies to present a more comprehensive understanding towards urban comfort and the influence of cultural and habitual variables (Cohen et al., 2013; De Dear, 2004; Kantor et al., 2012; Lin & Matzarakis, 2008; Nikolopoulou & Lykoudis, 2006). The adaptive approach can explain the crucial discrepancies within the comfort temperature range between cities sharing the same climate, and sometimes between two different zones located in the same city.

From the perspective of urban planning, thermal comfort/discomfort and heat stress are decisive parameters influencing the use of outdoor spaces which can be translated into the improvement of quality of life (Ali-Toudert et al., 2005; Aziz et al., 2011; Epstein &

Moran, 2006; Nikolopoulou et al., 2001; Nikolopoulou & Lykoudis, 2006). Therefore, strategies to mitigate UHI which subsequently improve the outdoor thermal environment is likely to prevent HRI while elevating the comfort level of urban communities. The literature review on UHI mitigation is elaborated in the following section.

2.5 Urban heat island mitigation studies via urban ecosystem management

Urban ecosystems are important because they accommodate daily pedestrian traffic and various outdoor activities that encourage the growth in both social and economic aspects besides contributing greatly to high-quality urban liveability and vitality. From a microclimatic point of view, the planning of urban ecosystem needs an approach to ensure ideal thermal comfort conditions (Blocken et al., 2012; Nikolopoulou & Steemers, 2003). Satisfying OTC level is considered as an essential part of sustainable urban development (Coccolo et al., 2016). Urbanites that are using the open spaces in a city needs an environment with promising thermal comfort to perform their activities (Mazhar et al., 2015; Patz et al., 2005). Otherwise, conditions which are not ideal would affect social activities and the economic aspects of these areas as well (Hajat et al., 2007).

Accelerated urbanization has led to the changes in the natural air movement, prevailing wind speed and direction, as well as solar radiation levels in major cities around the world (Givoni, 1998; Kawamoto, 2015). Urban design and planning professionals should integrate atmospheric information into design guidelines and urban planning regulations to minimize the deleterious climatic impacts on urban communities. However, the integration of such climatic aspects into the planning and design process is challenging due to the poor understanding of outdoor thermal indices and a need for interdisciplinary nature partnership between subject experts and urban planners (Elnabawi et al., 2016; Fahmy et al., 2008; Nouri et al., 2018; Oke, 2004; Shooshtarian et al., 2018). As a result, the application of these principles fits poorly in urban areas leading to uncomfortable outdoor conditions in various cities (Baker et al., 2002; Johansson, 2006). The projected increase in the frequency and intensity of heatwaves across global and regional scales highlights the importance of immediate preventative and adaptive measures (Ganguly et al., 2009). High-risk areas such as cities play a key role in climate change adaptation and mitigation because of the high concentration of assets, people and economic activities (Cortekar et al., 2016). Researchers found that the preventive approaches are most effective if they are applied in the community level (Anderson & Bell, 2009) especially with the increasing number of vulnerable population due to the UHI effects.

Urban ecosystems which were properly planned reduces the possible thermal stress and encourages people to participate in a higher number of outdoor activities (Nikolopoulou et al., 2011). By understanding how urban communities perceive the urban thermal environment, the findings can be used to reduce the overheating phenomena in urban areas by recommending proper urban planning (Salata et al., 2016) such as the appropriate material selection for the improvement of urban outdoor spaces (Salata et al., 2015; Santamouris et al., 2012; Tan et al., 2010).

A city needs to revisit its approach towards urban ecosystem management to solve the issue of UHI which is related to poor urban planning. The implementation of different mitigation strategies is considered to be one of the most commonly proposed solutions. Some of them are mutually connected and tend to use surfaces with a high albedo coefficient (Akbari et al., 2001b; Asaeda et al., 1996), surfaces that promote evapotranspiration (Saneinejad et al., 2014), vegetation (Alexandri & Jones, 2008) and trees (Klemm et al., 2015; Mahmoud, 2011; Park et al., 2012a; Rosenfeld et al., 1998; Shahidan et al., 2010). In a general prospect, the UHI mitigation strategies can be classified into two which are urban design and urban greening approach.

2.5.1 Urban heat mitigation strategies via urban design and greening approach

From the perspective of urban planning, studies from different countries and climate have shown that urban design and greening is a promising way to address UHI impact in urban areas. The common parameters considered in urban design and greening approach is elaborated in the following sections.

2.5.1.1 Urban design

Over the past few decades, making urban ecosystem attractive to people and encourages the usage of it has been increasingly recognized as a goal in urban planning and design. Such an effect emphasizes the important role of urban planners and urban designers in creating a favourable urban microclimate from the early design stage. Urban design is a fundamental problem-solving activity that determines the quality of the built environment where its objective is to meet the basic human needs for security and sociability (Hall, 2008). As a process, urban design is a means of organizing space in a city (Hall, 2008). Integrating the climatic considerations into urban planning and design would contribute significantly to the sustainable urban development and mitigate the adverse effects of increased urban surface air temperature. The common parameters considered in urban design is elaborated as follows.

(a) ***Urban morphology***

The morphology of an urban area is defined through various parameters. One of the key parameters in determining urban canyon geometry is the aspect ratio (AR), which is defined as the ratio between the average height (H) of the canyon walls and the canyon width (W) (Aboelata, 2020; Oke, 1988). The illustration of AR is presented in Figure 2.5.

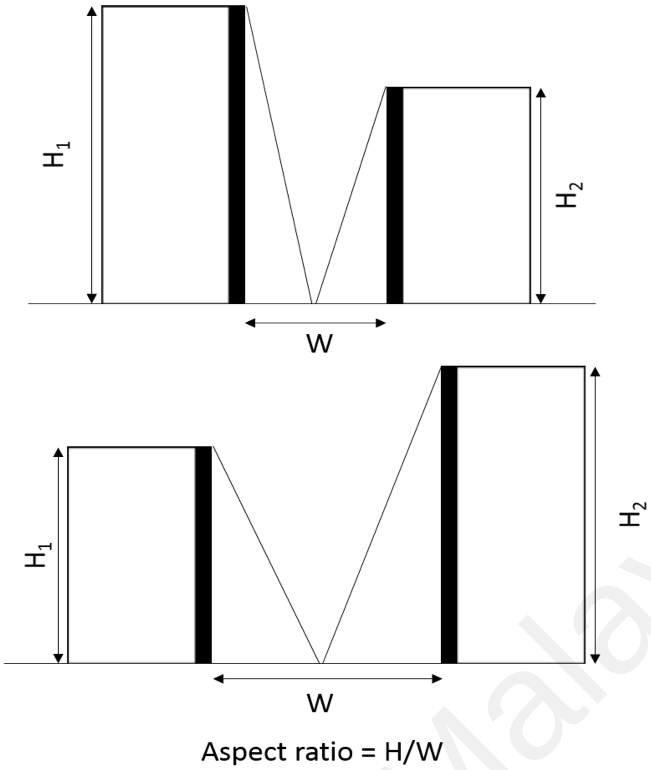


Figure 2.5: Illustration of aspect ratio (H/W)

The canyon is considered uniform if it has an AR approximately equal to 1, shallow if the canyon has an AR below 0.5, and deep if the AR equals 2. Nighttime air temperature has been directly linked to the magnitude of the AR, which means that higher AR would result in higher nighttime air temperature (Arnfield, 2003; De et al., 2018; Oke, Johnson et al., 1991). Besides that, radiative losses and penetration of the undisturbed wind are found to be lessened in deep canyons (Brown & Gillespie, 1990; Holmer, 1992; Jamei et al., 2019; Lai et al., 2019; Niachou et al., 2008; Oke, 1981). Research also shows that shading is the main reason behind the reduced level of thermal discomfort in tropical cities (Qaid & Ossen, 2015). Narrow streets surrounded by buildings are known to provide better shading for pedestrians on sidewalks as compared to wide streets. A simulation study in five different locations in Colombo, Sri Lanka indicated that deep street canyons with highly shaded streets present the greatest potential in ameliorating heat stress at outdoor urban spaces in a hot-humid climate (Hwang et al., 2011). Deep canyons were also found to have lower air temperatures and offer more favourable thermal condition for pedestrians during summer because of the lower level of exposure to the sun (Johansson & Emmanuel, 2006).

As one of the determinant factors of urban canyon geometry, AR is also capable to control the air movements at the pedestrian level. Urban canyons which can channel wind like natural canyons is crucial in enhancing wind speed and dissipating excess heat from urban areas. Therefore, wind patterns which are highly governed by the placement, geometry, and shape of the built-up and open areas in the city can be regulated via urban canyons. In a study conducted in Muar, Johor, Rajagopalan et al. (2014) simulated the effect of urban geometry and wind flow on UHII and found an improvement to the overall natural ventilation and thermal comfort at the pedestrian level by distributing the wind evenly along the leeward side of the buildings (Rajagopalan et al., 2014). Their findings ascertain the cooling benefits of the wind for the reduction of heat islands and thermal stress in cities.

Besides AR, the sky view factor (SVF) is also commonly associated with urban morphology (Tan et al., 2016). SVF is defined as the ratio of the amount of the sky which can be seen from a given point on a surface (Watkins et al., 2007). Buildings and vegetation are commonly found obstacles in an urban area which defines the level of SVF (Correa et al., 2012). SVF is a dimensionless number between 0 and 1, and it is an important parameter in characterizing the geometry, density, and thermal balance of urban areas. The illustration on SVF is presented in Figure 2.6.

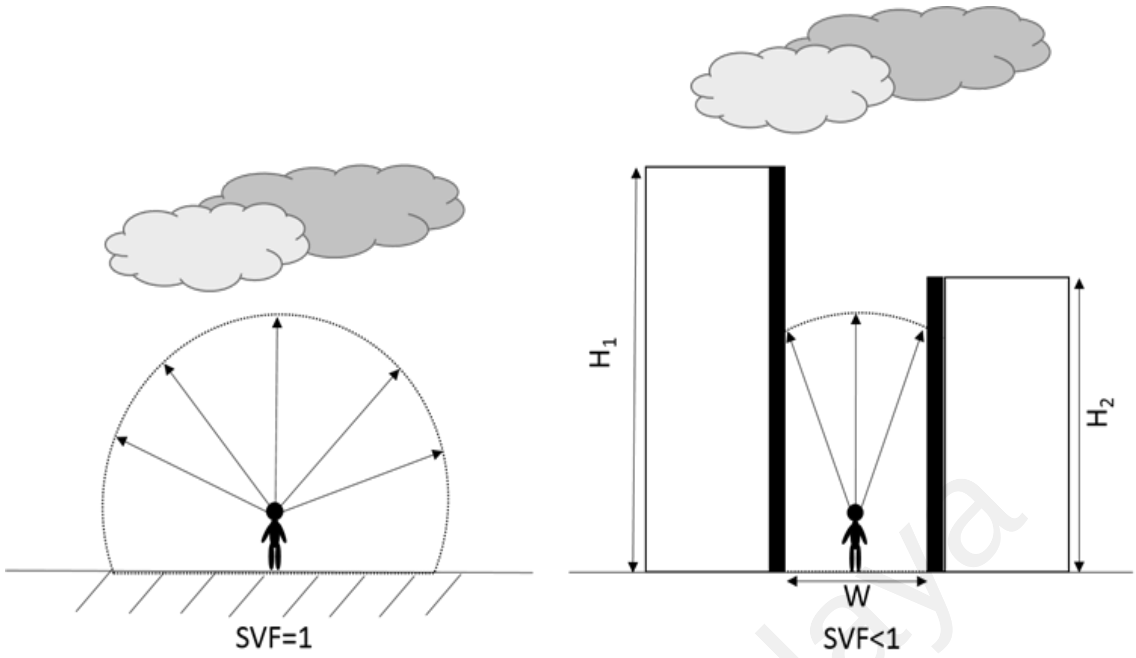


Figure 2.6: Sky view factor in an open space and a space surrounded by buildings

SVF has a strong influence on the absorbed and re-emitted solar radiation (Chen et al., 2012). Therefore, lower SVFs in urban planning could provide shading enhancement to ameliorate thermal discomfort, especially during summer periods. The compact urban configuration will result in less exposure to direct, diffused and reflected radiation at the pedestrian level. Since the neighbourhood is a smaller unit of a city, climate-based adaptive planning at this scale will help urban planners to create a comfortable living environment at the city scale. However, it should be highlighted that the alteration towards the AR or SVF to improve the urban environment may not be entirely practical because of various reasons such as high expenditure costs, issues with environmentally sensitive or protected areas, and the lack of information to carry out site-specific modifications.

(b) ***Street orientation***

Street orientation is another parameter that can influence the solar access in urban canyons and are therefore significant in defining the thermal environment in sidewalks at different geographical locations. Few studies that were carried out in tropical cities to identify the effect of street orientation on thermal comfort concluded that East-West (E-W) oriented streets experience the worst thermal condition during the day (Qaid & Ossen, 2015; Yang et al., 2016). E-W oriented streets was found to suffer from a prolonged period of solar exposure during the summer as compared to North-South (N–S) oriented streets which recorded slightly better thermal condition. The cooling potential of N-S oriented streets was also found to increase in wider canopies.

Besides influencing solar exposure, street orientation is also a decisive parameter with regards to air velocity in urban canyons. When the wind direction is parallel to the street axis, an obstacle-free passageway is developed such that the prevailing wind penetrates the urban canyon. Wind speed of 1–1.5 m/s is found to be able to reduce air temperature by almost 2°C (Radfar et al., 2012). A desirable orientation depends on the climatic type, the need for sun or shade, and a cool breeze or wind shelter. In short, the orientation of the street to the sun affects solar heat gains and ambient air temperatures while the orientation of the street concerning the wind affects ventilation heat losses.

(c) ***Building and surface materials***

Albedo is a parameter commonly related to the physical or chemical properties of building and surface materials. By definition, albedo is measured as the reflection coefficient which is the incident radiation that is reflected from the earth surface (Edwards, 2003; Taha, 1997). High albedo material could reduce the amount of solar radiation absorbed through building envelopes and urban structure (Taha, 1997). In return, high albedo materials can keep these surfaces cooler. Various studies have been conducted to identify the potential of high albedo materials in mitigating urban heat. For example, Song and Park (2015) conducted their research in Changwon City, South Korea while O'Malley et al. (2015) conducted their research in London, United Kingdom (O'Malley et al., 2015; Song & Park, 2015). In another study, Taleghani et al. (2014) increased the albedo of the bare courtyard in the university campus of Portland, United States of America, and found a decrease in air temperature by 1.3°C (Taleghani et al., 2014). There are also researchers such as Kim et al. (2016) who studied the suitability of materials with different albedos such as asphalt, soil, grass, water bodies and forest for the different urban surfaces in Seoul, South Korea (Kim et al., 2016).

Besides that, there is also considerable interest in the field of material science which forms the urban texture in various climates. For example, Yang and Lin (2016) experimented with a new type of bricks in Tainan, Taiwan (Yang & Lin, 2016), while Salata et al. (2015) tested a new covering for walls and ground surface in Rome, Italy (Salata et al., 2015). In another study, Benrazavi et al. (2016) examined the role of different pavement materials on urban heat reduction in Putrajaya, Malaysia (Benrazavi et al., 2016). Under shaded location, the Blue Impala polished granite pavement was found to exhibit significant surface temperature reduction of 15.6% between 9.00 am to 12.00 pm and 13.7% from 12.00 pm to 3.00 pm (Benrazavi et al., 2016). This study also provided evidence and highlighted that the material's thermal behaviour varies according to location and time.

Various studies have shown that high albedo materials would be beneficial in urbanized areas and can be implemented through the replacement of existing roofing and road materials with those of high-albedo characteristics. A careful selection of building and surface materials in an urban area would be most beneficial at the early stage of urban design and planning to assist the efforts in urban temperature reduction. However, to ease the burdening cost of replacing existing building and surface materials, the albedo in a city can be increased in stages by replacing darker materials with solar-reflective materials during routine maintenance of roofs and roads (Ibrahim et al., 2014; Rosenfeld et al., 1998).

2.5.1.2 Urban greening

The suggestion to implement urban greening in a tropical city has been proposed as early as in 1989 (Ibrahim & Samah, 2011). Relevant literature indicated that application of vegetation in urban areas would alter microclimate parameters (Tan et al., 2016) such as air temperature (Chen & Wong, 2006; Wong & Yu, 2005), relative humidity, wind pattern and precipitation (Byrne et al., 2008). A green canopy layer is also found to be effective in maintaining the thermal comfort of inhabitants by moderating environmental heat (Cheung et al., 2020; Ibrahim, 2014). Besides that, urban greening introduced to the urban environment is also capable to reduce ambient air pollution level (Jim & Chen, 2008; Jim & Chen, 2009). It was found that the leaves of the plants can absorb the gaseous pollutants, while soil microbes can breakdown the particulate matter (Asmat et al., 2008).

Urban greening is popular solutions for mitigating UHI effect (Fan et al., 2019; Yang et al., 2020; Yu et al., 2018) as shown through studies conducted in both temperate (Kikuchi et al., 2007; Narita et al., 2008; Park et al., 2012b; Tsiros, 2010) and tropical regions (Cheung et al., 2020; Mirzaei, 2016; Shahidan et al., 2012b; Wong & Jusuf, 2010; Wong et al., 2016). This is because urban greening can provide shelters and shades, while lowering the temperature in the urban areas (Givoni, 1991; Gonçalves et al., 2019; Roth, 2013; Takács et al., 2016). The role of vegetation on urban temperature reduction often gain the interest of local researchers although the use of different pavement materials and architectural innovations are occasionally studied as viable remedies as well. However, cities are considered hostile environments for greenery because of the high level of impervious surfaces, reduced level of soil moisture, lack of nutrient and rooting volume, and presence of air/water pollutants (Craul, 1985; Pataki et al., 2011; Peters et al., 2010). In agreement to Aflaki et al. (2016) and Phelan et al. (2019), future studies need to focus more on the creative and innovative use of greeneries in the form of green roofs, green façades, green corridors and green pavements to reduce the intensification of UHI effects in a city (Aflaki et al., 2017; Phelan et al., 2019). Apart from this, an adequate number of such studies are essential to provide enough fundamental data to determine the economic feasibility and social acceptance of the implementation of such strategies in the local context.

(a) ***Street trees***

Street trees can modify the microclimate by altering the solar radiation and terrestrial radiation from the ground through a shading mechanism (Fahmy et al., 2010). Shading was identified as one of the key factors in improving the urban thermal environment by reducing summer air temperatures and mitigating UHI from cities (Wong & Yu, 2005; Zaki et al., 2020). The shading provided by street trees reduces atmospheric temperature by actively intercepting incoming solar radiation thus preventing the rise of near-surface temperature. Therefore, increasing urban areas covered by trees will bring benefits to the shaded areas (Sawka et al., 2013). For example, street segments with trees in the tropical city of Bangalore, India, was found to show lower ambient air temperature by 5.6°C on average (Vailshery et al., 2013). Besides that, studies also found substantial energy saving by providing shade trees next to buildings. Shading which reduces the surrounding air temperature would also cause a reduction in the use of air-conditioning (Akbari et al., 2001a). Apart from shading, the evapotranspiration process of trees is also important in regulating urban heat. The absorbed solar energy causes an increase in the latent heat which expedites the process of water loss from a plant into the atmosphere through evaporation thus cooling the leaf as well as the temperature around the leaf (Taha et al., 1988). Street trees are also found to be beneficial to the environment by filtering air pollutants, reducing ambient noise level and stabilizing soil content.

Despite the proven track record in providing various environmental benefits, the quality of the shading effect and evapotranspiration rate of a tree depends on several factors such as the total height, canopy geometry, foliage characteristics and shape of the tree (Santamouris & Asimakopoulos, 2001). The shading quality was also found to vary from one species to another (Brown et al., 1995). Shading is generally evaluated based on the type, size and density of the foliage as well as the arrangement of the branches and twigs because they are influencing factors in absorbing radiation and reflection through the canopy layer. The quantification of these characteristics is commonly done by evaluating the Leaf Area Index (LAI), which is expressed as a dimensionless value of the leaf area per unit of the ground area (Montague & Kjelgren, 2004). LAI provides a common ground to compare various tree species and plant canopies about their ability to filter incoming solar radiation. Trees with larger LAI and higher density is expected to contribute to the lowering of radiant heat and the amount of terrestrial radiation underneath the canopy layer.

Apart from the different LAI of each tree species, the tree’s capacity to tolerate heat and drought has a compelling influence on the cooling potential of a tree (Leuzinger et al., 2010; Specht & Specht, 1999). Besides that, the ability of street trees in providing a better thermal condition for pedestrians is also influenced by surrounding infrastructure development, maintenance issues, poor water availability as well as urban geometry characteristics (Lin et al., 2008) such as building heights, density and surface materials in an urban area. Cooling benefits of street trees are found to be highly localized and distinguished according to spatial and temporal variation (Cheung et al., 2020). For example, Onishi et al. (2010) found that planting greeneries in different land-use and land-cover types have a varying impact to reduce surrounding temperature across seasons (Onishi et al., 2010). On top of that, the ability of the vegetation to alter the air movement and advection is also known to be largely dependent on the vegetation type (Bonan, 1997). For example, a deciduous tree can reduce wind speed by 30–40% (Ali-Toudert & Mayer, 2007a). Therefore, trees can have either a cooling or warming effect depending on their position in the city, the prevailing wind conditions and time of the day.

(b) ***Urban parks***

The effect of a single tree in moderating the microclimate is well-documented, but this effect is limited to the microclimate at a specific point (Oke et al., 1989). However, large urban parks have significant cooling effects, extending toward the surrounding built environment (Chen & Wong, 2006). Urban parks if appropriately designed, can also significantly negate the extreme danger of heatwaves (Liu et al., 2020). Infrared photographs along a green pedestrian canyon in Singapore showed that large urban parks appeared as "cold spots" and thus confirming the potential to mitigate local UHI impact (Forsyth et al., 2005). In another study, Chang & Li (2014) found that urban parks were cooler on average than their surroundings, confirming the term "urban cool islands" (Chang & Li, 2014). The low daytime air temperatures monitored in urban parks are attributed to increased evapotranspiration and solar shading, whereas nighttime cooling effect contributed to the increased radiative cooling potential and substantially lower convective heat released. This urban cooling effect may also be attributed to the high absorption capacity of the green canopy layer on the incoming solar radiation (Cheung et al., 2020; Ibrahim et al., 2012).

The thermal benefits of urban parks are dependent on the thermal balance between the overall area under study and distance from the park. The cooling benefit is found to be highly localized and rapidly diminished by increasing the distance from the edge of the urban parks. In one related research, Buyadi et al. (2014) studied the influence of land cover profile on urban cooling and deduced that about 3.17°C of cooling intensity provided by the green areas was only significant within 500 meters from the parks (Buyadi et al., 2014). Besides that, studies have also shown that the cooling effect was more substantial as the area of the park was larger. Nevertheless, field studies were able to show that small parks could also significantly provide an urban cooling effect. In an attempt to enhance the microclimate and thermal comfort in an urban park in Shah Alam, Nasir et al. (2015) found that the dense and matured trees sustained the microclimate of the park by lowering air temperature by a maximum of 0.2°C and mean radiant temperature by a maximum of 15.8°C (Nasir et al., 2015). In another study conducted in Putrajaya, Ahmed et al. (2015) found that clustered trees were effective in reducing 9% of the surface temperature as compared to scattered and isolated trees (Ahmed et al., 2015).

(c) ***Vertical greenery system (Green façade and green roof)***

Recently, there are increasing studies carried out by urban planners and architects to incorporate greening in a vertical motion to address the lack of space in urban areas for vegetation. The implementation of vertical greenery system is most observable through green façade on buildings as well as standalone structures. Besides exploring the implementation of green façade in an urban area, there are also studies conducted to identify the potential of these green façade in ameliorating urban heat. For example, Jänicke et al. (2015) studied the thermal behaviour for a facade greening in the campus of the Berlin Institute of Technology, Germany. It was found that greened façade was able to provide an average decrease in mean radiant temperature by about 2 K (Jänicke et al., 2015). Besides that, in a study conducted in Hong Kong, the green-wall applied was able to achieve an average cooling of 8.5°C as compared to the bare wall surface on sunny days (Lee & Jim, 2020). This highlighted the potential of green façade to be used in modern urban design to reduce urban heat impact as well as to reduce building energy consumptions.

Besides green façade, green roofs are also popular alternatives to integrate vegetation in an urban area which do not compromise space for other land use. Green roofs are also recognized as an effective sustainable design tool to mitigate UHI effects (Lee & Jim, 2020; Peng & Jim, 2013). Unlike green façade, there are more studies with regards to the potential of green roof in sustainable urban development. A green roof or roof garden is defined as roofs that consist growing medium that supports vegetation (Asmat et al., 2008; Lepp, 2008) and is known as passive methods in reducing building energy consumptions and thermal performance in buildings (Asmat et al., 2008). By introducing vegetation to large roof surfaces, green roofs were able to contribute to the improvement of the building's thermal performance (Eumorfopoulou & Aravantinos, 1998; Lee & Jim, 2020; Tian et al., 2017). A well-designed and managed green roof could behave like a high-quality insulation mechanism to reduce the heat flux through the roof in summer (Barrio, 1998; Tian et al., 2017). The research found that the indoor temperature of a building with a green roof was lower during the day (Niachou et al., 2001). In another study on the thermal performance of extensive rooftop greenery systems in Singapore, Wong et al. (2003) discovered that over 60% of heat gain was prevented by the implementation of the green roof system as compared to the original exposed roof surface (Wong et al., 2003).

Therefore, a green roof can effectively reduce the need for artificial cooling using air conditioning especially in the hot summer (Liu & Baskaran, 2003; Spala et al., 2008). Ultimately, a green roof would be able to contribute to energy saving potential (Lee & Jim, 2020; Niachou et al., 2001; Shufro, 2005) and the reduction in greenhouse gases. A green roof can also significantly extend the life of a roof surface by protecting the roof membrane with a series of layers that can minimize the harm from extreme temperature fluctuations and ultraviolet rays (Asmat et al., 2008).

In summary, implementing urban greening via green façade and green roofs have been proven to be effective in terms of adding vegetation to a confined space in an urban area. Through various studies, the potential of these measures in ameliorating urban thermal stress was found to be promising across different cities and climates. However, such studies are found to be still lacking in a tropical context. It is important to note that, the practical evaluation of UHI mitigation strategies may be very costly and tedious. Therefore, modelling and simulation approach of UHI mitigation strategies via software such as ENVI-MET could serve as preliminary studies before carrying out physical changes. In the following section, the literature review on ENVI-MET software is presented.

2.5.2 Exploring urban heat mitigation strategies via ENVI-MET as a microclimate simulation tool

The creation of sustainable cities was never achieved through market forces alone nor top-down urban planning. Cities are currently experiencing more complicated problems with the urban environment that requires a solution beyond traditional thinking and design approaches (Dave, 2012). The findings from a holistic approach towards urban planning do not always yield meaningful results due to the limitations in models or a thorough understanding of the underlying factors (Schmitt, 2012). As a result, it is crucial to combine contemporary instruments and methods or even to develop state-of-the-art technologies which allow reliable simulation of scenarios for sustainable future cities (Bettencourt & West, 2010). Through various studies, the software ENVI-MET has shown to exhibit promising reliability with the simulation of the urban microclimate by considering the surface-plant-air interactions in urban environments (Bruse & Fleer, 1998; Qaid et al., 2016, 2014; Ramakreshnan et al., 2018). On top of that, few studies have also demonstrated its capabilities in exploring various urban design and greening towards the improvements in urban climate across various countries.

2.5.2.1 ENVI-MET as a micro-climate simulation tool

ENVI-MET is a prognostic three-dimensional (3D) microclimate model that is designed to simulate the surface-plant-air interactions in urban environments (Bruse & Fleer, 1998). Based on the laws of fluid dynamics and thermodynamics, ENVI-MET models the evolution of climate variables during diurnal cycles by combining the influence of buildings, vegetation, surfaces characteristics, soils and climatic contour conditions (Bruse & Fleer, 1998). The software is capable to calculate and simulate climate variables by considering a complete radiation budget of direct, reflected, diffused solar radiation and longwave radiation in the study area with a typical grid resolution of 0.5 to 10 m in space and 1 to 5 seconds in time (Bruse, 2009; Salata et al., 2016). The ENVI-MET model consists of five model groups which are summarized in Table 2.3.

ENVI-MET is based on a 3D computational fluid dynamics (CFD) model. For each spatial grid cell and time step, the CFD model solves the Reynolds-averaged non-hydrostatic Navier-Stokes equations. Turbulence is calculated using the 1.5th order closure k-ε model. Two prognostic equations are used to solve the kinetic energy in the turbulence (k) and the turbulent dissipation (ε). In consequence, these two equations represent the turbulent properties of the flow (Jones & Launder, 1972). For initialization of simulation, meteorological input such as wind direction, wind speed (measured in 10 m above ground level), relative humidity, air temperature, specific humidity and cloud coverage (optional) have to be provided. For specific humidity information, values from 2500 m above ground level have to be provided whereas all other parameters can be obtained from ground-based measurements using instruments such as a weather station.

Table 2.3: The model groups within ENVI-MET

Model groups	Descriptions
Atmospheric model	Calculates the air movement, three-dimensional turbulence, temperature, relative humidity and considers obstacles such as buildings and vegetation. The maximal height of the model is 2500 m. The variation of radiation due to vegetation and shading is also considered.
Surface model	Calculates the emitted longwave, and the reflected short-wave radiation from the different surfaces, considering the incident long and shortwave radiation. It considers the albedo of the surfaces, the shading in the function of the solar path and calculates the water vapour evaporation from the vegetation and the transpiration from the soil, considering the air flow-modifying effect of the vegetation. It is adapted to model flat surfaces.
Vegetation model	Calculates the foliage temperature and the energy balance of the leaves considering the physiological and meteorological parameters. The vegetation is characterized by the normalized leaf area density (LAD) and the normalized root area density (RAD). The evaporation rate and the turbulence calculation are based on the airflow fields around the vegetation and the tree shape. The evaporation rate at the leaf surface, regulated by the stomata, is affected by the heat exchange between the leaf and its environment. The absorption characteristics of the foliage are calculated in function of the sun path and the projected shade.
Soil model	Calculates the thermal and hydrodynamic processes that take place in the soil. This model considers the combination of the natural and artificial surfaces of the urban quarter considered and it can also calculate heat exchanges between a water body and its environment.
Bio meteorological model	Calculate the thermal comfort indices based on meteorological data.

In the research community, ENVI-MET is widely used in the context of human biometeorology and thermal comfort studies (Ali-Toudert & Mayer, 2007b; Ambrosini et al., 2014; Chen & Ng, 2013; Ghaffarianhoseini et al., 2015; Jänicke et al., 2015; Taleghani et al., 2014). The simulation capability of ENVI-MET is also proven useful to study the effect of urban design such as street design (Yang et al., 2016; Yang et al., 2016) and street aspect ratio (Yang et al., 2015) on urban microclimate. ENVI-MET has been widely used and tested intensively for different aims in different climate regions (Ali-Toudert & Mayer, 2006; Chen & Wong, 2006; Huttner et al., 2009). The capability of the ENVI-MET software for urban heat mitigation studies is elaborated in the next section.

2.5.3 Case studies using ENVI-MET to simulate urban heat mitigation

There is a rise in research using ENVI-MET software to evaluate the bio meteorological conditions in an urban layout (Salata et al., 2016). In a study carried out in Stuttgart, Germany, Ketterer and Matzarakis (2015) simulated a decrease in the PET value of 0.5°C at 10:00 pm due to an increase in the number of trees (Ketterer & Matzarakis, 2015). Besides that, ENVI-MET software is also used in various UHI studies to examine the influence of urban design and greening on micrometeorological variables. For example, Lee et al. (2016) estimated how trees and grasslands affect the microclimate of a typical residential area in Freiburg, Germany, while Martins et al. (2016) pointed out the major influence of vegetation on the mitigation of UHI in Toulouse (Lee et al., 2016; Martins et al., 2016). In another study at São Paulo, Brazil, Duarte et al. (2015) simulated the thermal performance of small parks characterizing the urban texture and trees on the edge of the street (Duarte et al., 2015). In a similar study, Skelhorn et al. (2014) discovered an increase of 5% in mature deciduous trees can decrease the average surface temperature by about 1°C in Manchester, the United Kingdom during summer (Skelhorn et al., 2014). For an urban regeneration program in Pechino, China, Wang and Zacharias (2015) simulated a decrease in the air temperature ranging between 0.5°C to 1.0°C if a section of the road infrastructures were substituted with vegetation and permeable soils (Wang & Zacharias, 2015).

In other studies, researchers would opt for a case scenario approach comparing the performance of several scenarios with the existing configuration. For example, Tsilini et al. (2015) examined the potential of three configurations (without vegetation; with horticulture plants; and with aromatic and medicinal plants) against the current configuration to reduce the surface temperature in Chania, Greece (Tsilini et al., 2015). By implementing horticulture plants or aromatic and medicinal plants in the study area, Tsilini et al. (2015) simulated a decrease in the surface temperature by 10°C as compared to the existing configuration. In another study conducted in Oberhausen, Germany, Müller et al. (2014) identified the most effective UHI mitigation strategy is the one with parks characterized by high trees with distinct crown layer and able to provide shading without obstructing wind activity (Müller et al., 2014). Similarly, Morakinyo and Lam (2016) examined different values of green coverage represented by LAD and LAI on the thermal performance in an urban area in Hong Kong (Morakinyo & Lam, 2016). Likewise, in Hong Kong, Tan et al. (2016) examined the effect of tree orientation towards mitigating daytime UHI. A similar study was also carried out in Phoenix, United States of America by Middel et al. (2015) by simulating different scenarios with varying canopy cover from 0% to 30% (Middel et al., 2015). It was found that every per cent increase in canopy cover will result in a decrease of 0.14°C in air temperature.

In short, the ENVI-MET software has a proven track record of simulating various urban design and urban greeneries towards the understanding of their influence towards the microclimate and mitigation of UHI. As shown through various research in cities around the world, it is promising to undertake a similar approach to simulate various UHI mitigation strategies in a tropical city such as KL before carrying out physical changes to the urban ecosystem. While countries from different climates are struggling to achieve a balance in urban design for both summer and winter, the urban design and greening approach in a tropical climate are much straightforward. Hence, immediate measures must be taken to ensure that the impact of climate change can be minimized through effective urban design and greening approaches. In the following section, the knowledge gap of UHI research in Malaysia is presented.

2.6 Urban heat island research in tropical Malaysia

As opposed to a remarkable accumulation of observational heat island studies in temperate climates, the UHI studies in the equatorial, tropical and sub-tropical settlements are scanty (Arnfield, 2003; Ramakreshnan et al., 2018). The understanding of the UHI phenomenon in the tropics is important as the UHI phenomenon varies according to the climate and region although sharing similar urban morphologies. For example, studies revealed that smaller SVF in the tropical regions is deemed effective in the mitigation of urban heat while larger SVF is preferred in the temperate regions instead (Wong, 2016). Similarly, UHIs contribute to thermal discomfort and higher energy loads in mid- and low-latitude countries, whereas it can function as an advantage in reducing heating loads in cooler climates (Rajagopalan & Wong, 2012). A thorough understanding of the UHI phenomenon in a tropical climate would be able to cater to the high population growth with socio-economic significance without compensating too much on urban liveability. Besides that, the UHI phenomenon in a tropical city is unique because the microclimate is greatly influenced by high solar radiation, air temperature and humidity throughout the year.

Malaysia is envisioned to be among the top twenty most liveable cities in the world by the year 2020 besides being economically established (Economic Planning Unit, 2013). Yet, the rapid urbanization over the past few decades have led to the deterioration of the natural and built environment, particularly in major city centres like KL. Recently, the urban heating phenomenon received considerable attention as the country irregularly experience many devastating consequences of rising temperatures such as heatwaves (Ibrahim et al., 2014; Othman et al., 2016), chronic water shortages (The Star Online, 2016b), flash flood (Akasah & Doraisamy, 2015; Ibrahim et al., 2012; Kondoh, 2007), torrential rain (Gasim et al., 2014) and even rare episodes of hail storms (The Star Online, 2016a). This is a consequential issue for KL as a fast-growing tropical urban conurbation owing to its crucial role as an engine of economic growth for Malaysia. Notable attention was garnered after KL was described as getting hotter by 0.6°C per decade which is the world's highest value so far reported for the UHI effects (Davis et al., 2005). However, studying the urban heating phenomenon in Malaysia and the related consequences through a retrospective approach is challenging due to the lack of continuous measurements and studies in this region.

The first groundwork for the assessment of UHI in a tropical city was initiated in the late 1960s by Nieuwolt in Singapore (Amanollahi et al., 2016; Roth & Chow, 2012). In 1970, Sani (1972) conducted the first comprehensive UHI study in KL, the capital of Malaysia. Sani (1972) conducted in-situ data collection for about two decades using temperature traverse method and discovered that the temperature distributions were higher in the built-up city centre of KL as compared to the surrounding rural areas (Sani, 1972, 1984, 1986, 1987, 1990). In 1985, Sani represented the temperature distributions in KL as isotherms and discovered that the UHII was greatest during calm and clear sky nights. Meanwhile, Sani also compared the intensity of UHI for four nights with similar weather conditions in 1972, 1975, 1980 and 1985 respectively. The recorded UHII from Sani's work is presented in Table 2.4.

Table 2.4: Recorded urban heat island intensities in 1972, 1975, 1980 and 1985

Year	Maximum Isotherm (°C)	UHII (°C)
1972	28.5	4.5
1975	28.8	4.4
1980	31.1	6.7
1985	28.0	4.0

In the last four decades, Malaysia has witnessed growing scientific studies to understand UHI along with its contributing factors, its subsequent impacts as well as the development of urban heat mitigation strategies. After Sani's work in the early 70s, more research related to the formation of UHI is conducted by researchers such as Elsayed (2012), Yusuf et al. (2014), Shaharuddin et al. (2009; 2014), Amanollahi et al. (2016), Salleh et al. (2013), Hashim et al. (2007) and Morris et al. (2015; 2016) in areas around Greater KL (GKL) with more attention given to the city centre of Klang Valley.

As observed over the two decades, the irregular pattern in the maximum temperature over a large area in Sani's work is associated with the weakness of point measurements. Besides, the increase of temperature associated with land-use changes is not reflected by the isotherms in KL that experienced rapid urbanization during the study period. Innovatively, Elsayed (2012) addressed the weaknesses of point measurements by combining both traverse temperature method with a network of weather stations to study the formation of heat and cool islands in the city of KL in 2004 (Elsayed, 2012a). An increase of 1.5°C in UHII was found as compared to Sani's finding in 1985. On top of that, Elsayed (2012) also discovered the emergence of more heat islands while many cool islands disappeared in the city centre due to the rapid land-use changes (Elsayed, 2012a).

The study also identified a shift of UHI nucleus from a decaying Chow Kit city towards the newly emerging Puduraya due to various human activities, population relocation, traffic congestion, construction and commercial activities during the time the study was conducted.

Despite the importance of conventional in-situ measurements in UHI studies, they are still poor in providing reliable spatial and temporal monitoring over a large area. Henceforth, a growing number of studies began to explore the application of satellite technology in determining the land surface temperature to quantify UHI in GKL. The satellite technology was also able to associate land use pattern with the surface temperature increment over the years which was lacking in previous studies. Often, satellite imagery is integrated with geospatial software such as geographical information system (GIS) because the more sophisticated analysis can be carried out. For example, Amanollahi et al. (2016) found that the increase in surface temperatures between the years 2000 (21.5°C) and 2010 (22.7°C) was related to the conversion of forests into urban areas in Klang Valley (Amanollahi et al., 2016). In another study, Hashim et al. (2007) discovered that rapidly developing areas in the southern region of KL such as Kajang, Cheras and Bandar Baru Bangi showed high surface temperatures (27.5°C) because of the introduction of impervious surface covers such as asphalt and concrete for road and infrastructure developments (Hashim et al., 2007).

Despite the limited use in local studies, SEB is also considered as an indicator of urban heating phenomenon (Rizwan et al., 2008). Through a simple SEB conducted over selected areas in KL with heavy concrete-made building structures, Tso & Law (1990) revealed that the maximum temperature at noon was due to heat absorption and storage by the concrete mass during intense solar radiation (Tso & Law, 1990). Besides that, more studies also begin to make use of numerical simulations in studying the UHI phenomenon.

For example, Morris et al. (2015) applied a single-layer urban canopy model coupled with the Weather Research Forecast/NOAH Land Surface Model in Putrajaya and discovered that the UHII varied temporally and spatially with a maximum magnitude of 3.1°C in 2012 (Morris et al., 2015). In another study conducted in 2014, Qaid studied the formation of UHI in Putrajaya, a city designed based on a garden city concept using ENVI-MET and was able to simulate the formation of UHI in detail (resolution of 20 m by 20 m) by considering the interaction between the meteorological parameters, vegetation and soil profile, building layouts, and human biometeorology conditions (Qaid et al., 2016, 2014; Ramakreshnan et al., 2018). Comparatively, software such as ENVI-MET can provide higher resolution of urban climate estimation as opposed to remote sensing because it is designed to cater micro-scale simulation that supports a horizontal resolution of 0.5 to 10 m and a typical time frame of 24 to 48 hours with a time step of 1 to 10 seconds (Bruse & Fleer, 1998; Qaid et al., 2016).

Since the 1970s, the methodological approach in quantifying UHI has shown to evolved drastically with the advancement in science and technology. With a bloom of UHI studies in 2012 after nearly two decades of paucity in UHI assessment, more studies are being conducted to identify the factors, impacts as well as urban heat mitigation strategies in a tropical city (Ramakreshnan et al., 2018). With the prominent impact from UHI and also from global climate change, the understanding of UHI in the tropics becomes much important as the threat is amplified in the tropical climate where it is hot and humid annually. As half of the world population is currently concentrated in the tropics (Siemens, 2011), escalating studies are focusing on identifying new strategies to enhance the urban liveability in tropical cities (Ignatius et al., 2015).

2.6.1 Contributing factors of urban heat island phenomenon in a tropical city

In a review of UHI research in GKL, Ramakreshnan et al. (2018) highlighted that there is a shift in research trend towards exploring major contributing factors and mitigation strategies of UHI rather than communicating UHII solely. In one of such studies, Buyadi et al. (2013) found that the conversion of 17.48% of vegetated lands into man-made urban materials contributed to an increase of 7.2°C in surface temperature over 18 years in Shah Alam (Buyadi et al., 2013). This study concluded that the reduction in vegetation density is one of the main contributing factors of UHI. In another study, Salleh et al. (2013) found that the surface temperature in Putrajaya increased steadily by 4.9°C between 1999 and 2006 due to heavy urbanization activities (Salleh et al., 2013). Eventually, due to the adoption of the garden-city concept in the urban design and greening practices, the surface temperature decreased (3.2°C) in the following years with a consistent increase of vegetation in the city centre. Similarly, in Putrajaya, Thani et al. (2013) found that the highest temperature (39.0°C) was recorded at the boulevard area with impermeable and paved surfaces while the forested land situated at the northern part of Putrajaya comparatively registered the lowest temperatures (32.5°C) during the study period (Thani et al., 2013).

Most of the studies in GKL mainly addressed vegetation depletion and land cover changes as the primary factors of the UHI phenomenon. Some studies also evaluated the contribution of urban configuration and surface/building materials on the amplification of UHI. However, intense and detailed studies on the thermal bulk properties of urban materials, surface radiative properties, anthropogenic heat production, air pollution and other urban geometric features are still lacking in the context of GKL. As discussed by Aflaki et al. (2016) and Manteghi et al. (2016), more advanced techniques such as CFD simulations and urban canopy models can be promising options to present the development, distribution, mitigation and the other unexplored contributing factors of

UHI (Aflaki et al., 2017; Manteghi et al., 2016). Due to the lack of studies, the total SEB in GKL was not fully understanding and remains a big challenge to UHI studies in a tropical city.

2.6.1.1 The impact from urban heat island phenomenon on KL

While the contributing factors of UHI are thoroughly studied, the impacts of UHI in GKL is given lesser attention because of its multifaceted complexity. Commonly, the priority to address the impact is set according to the level of influence on daily life. For example, water supply disruptions which affect daily domestic consumptions and business is often highlighted above other impacts. On the other hand, impacts which have consequences in longer periods such as deterioration of environmental quality and human health are poorly addressed.

2.6.2 Past research on OTC and heat-related health outcomes

2.6.2.1 Outdoor thermal comfort studies in Malaysia

Through a systematic review to identify the research gap in OTC assessment within the tropical climate of SEA, Fong et al. (2019) identified only 21 eligible studies between the years 1997 and 2016. The knowledge gap concerning OTC research in SEA is believed to be scarce where most of the studies are concentrated in Malaysia (10) and Singapore (6) while countries such as Indonesia (3), Vietnam (1) and Thailand (1) have three or lesser studies (Fong et al., 2019). In Malaysia, various OTC studies have been conducted using thermal indexes such as Physiological Equivalent Temperature (PET) (Makaremi et al., 2012; Nasir et al., 2012), Standard Effective Temperature (SET) (Kubota & Ossen, 2009) and Predicted Mean Vote (PMV) (Azizpour et al., 2013). Although several thermal comfort studies have been conducted in Malaysia previously, there are still many opportunities for a more in-depth study on OTC with a recently developed thermal index such as the Universal Thermal Climate Index (UTCI).

Besides that, it is also observed that the study area chosen for OTC studies in Malaysia are mainly located in lake gardens (Nasir et al., 2012; Nasir et al., 2013b, 2013a), recreational areas (Bakar & Gadi, 2016), and Putrajaya, a city built based on a garden-city concept (Din et al., 2014; Qaid et al., 2016). The high number of OTC studies in densely vegetated areas signifies that more studies should be aimed at areas which are densely built instead. For example, the Puduraya area which is characterized by high population and traffic congestion with various construction and commercial activities (Elsayed, 2012a). Besides that, future OTC studies can also be conducted in areas around Dataran Merdeka which was found to be the hottest among the 75 locations measured in KL city centre (Ibrahim & Samah, 2011). The OTC studies conducted in Malaysia are summarized in Table 2.5.

In a review, Ramakreshnan et al. (2017) highlighted the evidence of physical and psychological health impacts of haze in ASEAN countries (Ramakreshnan et al., 2017). Unlike health issues due to transboundary haze, the relationship between health issue and UHI in SEA or among ASEAN countries has remained unexplored. Through a review of socio-economic indicators for urban scale analysis, Ibrahim et al. (2017) stressed that urban health and well-being is not addressed in any previous urban climate studies in Malaysia (Ibrahim et al., 2017).

Table 2.5: Summary of outdoor thermal comfort assessment done in Malaysia recently

Year	Assessment approach	Study area	Researcher
2016	Evaluating PET at human height level through ENVI-MET software	Putrajaya	Qaid et al.
	Survey on thermal comfort and thermal sensation with collection of physical environmental data to identify thermal preference vote	International Islamic University Malaysia and Taman Melati Recreational area	Bakar et al.
	Assessment of UTCI using regression equation	Alor Setar, Kuantan and Subang	Hanipah et al.
	Assessment of PET using software and environmental data	Penang	Taib et al.
2014	Survey on thermal sensation conditions and calculations of Discomfort Index (DI) using temperature and relative humidity data	Putrajaya and University Teknologi Malaysia	Din et al.
2013	Survey on thermal perception and Apparent Temperature (AT) calculation using meteorological data as input	Shah Alam Lake Garden	Nasir et al.
	Survey on thermal sensation vote and evaluation of Heat Index (HI)		Nasir et al.
2012	Survey conducted to identify perception of climatology factors in outdoor activities		Nasir et al.
	Evaluation of PET and AT		Nasir et al.
	Survey on thermal comfort and evaluation of PET	University Putra Malaysia	Makaremi et al.

A significant lack of studies on human OTC in the tropics (Ahmed, 2003; Chow et al., 2016; Johansson & Emmanuel, 2006; Lin, 2009; Lin et al., 2010; Makaremi et al., 2012; Morris et al., 2017) and the lack of understanding of human health implications which arises because of UHI (Fong et al., 2019) suggests an urgent need for more scholarly studies. The knowledge of human biometeorology in urban planning is an important investment for the development of resilient cities and communities against global climate change soon (Ndetto & Matzarakis, 2017). Hence, the urban planners and designers must be well equipped with adequate knowledge on OTC to provide efficient urban designs that prioritize the functionality and usability of open space in a tropical city (Roth, 2007).

2.7 Summary

Anthropogenic activities have led to the occurrence of global climate change and the formation of UHI in rapidly developing cities. Since 1980, several studies have been dedicated to understanding the formation of UHI across various climates and cities in the world. The contributing factors causing the UHI phenomenon are commonly associated with the replacement of vegetated lands into impermeable surfaces with tall urban structures which causes a slower heat dissipation rate in the urban areas as compared to the rural fringes.

Throughout the years, various UHI assessment approach has been carried out. The UHI assessment approach has evolved from point measurements of air temperature to using a network of weather stations and satellite imageries to monitor the land surface temperature covering a larger area. Recently, there is also a rise in UHI studies conducted using refined modelling and simulation approach through computational fluid dynamic models such as ENVI-MET. While the impacts from UHI towards the natural environment is well documented, the resulting impact from UHI towards the health and well-being of urban communities are still lacking. There is also a rising concern in the deterioration of OTC level in cities due to the accumulated heat stress in urban areas. A systematic review conducted on the OTC research in the tropical climate of SEA revealed a low count of scientific research in this field. Most studies which were from Malaysia are conducted in densely vegetated areas or city which is developed based on a garden-city concept. The lack of studies in city centres where UHI are reported to be prevailing needs to be given attention in future studies.

Besides understanding the formation of UHI and the consequential impacts, there are also several studies dedicated to identify strategies to mitigate the deleterious impact from UHI. The improvement towards the urban environment can be effectively carried out via proper urban ecosystem management. Urban planners and subject experts have highlighted the crucial role of urban design and greening towards the enhancement of urban microclimate. The implementation of various urban design and greening characteristics is best investigated with a reliable model and simulation approach before conducting a real-scale application. As shown through numerous research and case studies around the world, ENVI-MET is deemed to be reliable software to study the impacts of urban design and greening towards the improvements in the urban environment. On top of that, more studies are needed to provide supporting evidence for stakeholders to actively implement urban heat mitigation approaches in line with existing policy and guidelines in Malaysia.

CHAPTER 3: METHODOLOGY

3.1 Introduction

A detailed description of the research methodology is presented in this chapter. The overview of the methodological approach used in this research is presented in Section 3.1.1.

3.1.1 Flow chart of research methodology

The research work began with a literature review to provide an overall understanding of the research topic. In general, the research is conducted in three phases. In the first phase, the research focuses on the variations of an urban microclimate through continuous monitoring of meteorological parameters at human height level. In the second phase, the research focuses on identifying the influence of urban heat towards the outdoor thermal comfort level and health implications towards the urban community in the selected study area. Lastly, in the third phase, the research focuses on the 3D urban microclimate modelling and simulation of urban heat mitigation measures based on the case scenario approach. Thesis writes up and publications commenced at the end of the research. The flow chart of the research is shown in Figure 3.1.

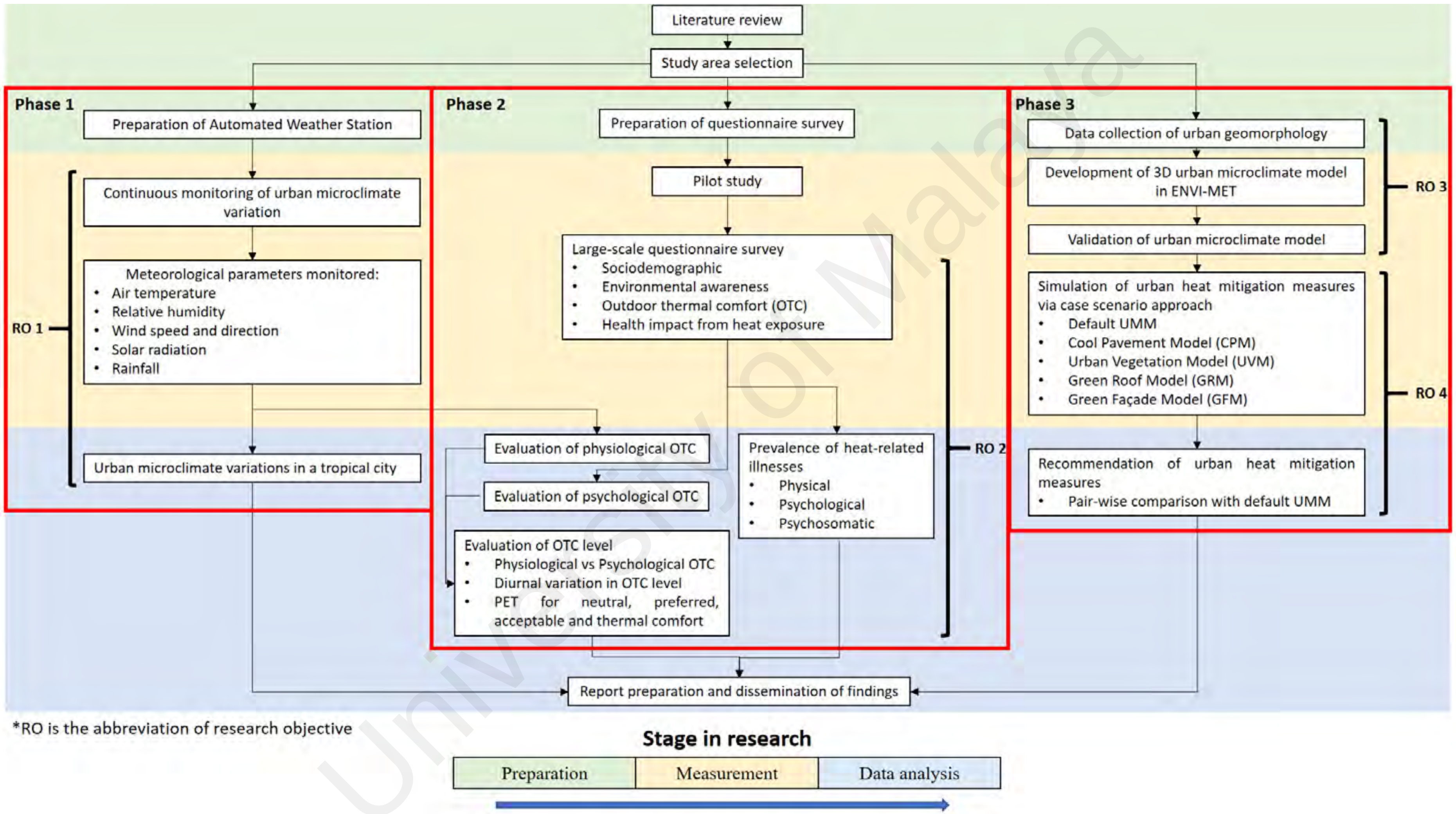


Figure 3.1: Research flowchart

3.1.2 Study design

An inter-disciplinary approach is undertaken to understand the complex interaction of urban heat with the natural environment, built environment and human health within a tropical urban setting. In specific, continuous monitoring is conducted to identify the variations in urban microclimate at the selected study area. Then, a cross-sectional approach is undertaken to explore the influence of urban heat towards human health implications. Finally, a 3D urban microclimate simulation model is developed and validated to identify potential urban heat mitigation measures to improve the urban microclimate in the selected study area.

3.1.3 Materials and equipment

The materials and equipment used in this research is elaborated in this sub-section.

3.1.3.1 Automated weather station

A unit of Automated Weather Station (AWS) was placed in the study area to collect meteorological data such as solar radiation, wind speed and wind direction, air temperature and relative humidity. The AWS model, Vantage Pro2™ (6152, 6153) along with its integrated sensors are made in the United States of America by Davis Instrument. The setup of the AWS is illustrated in Figure 3.2.

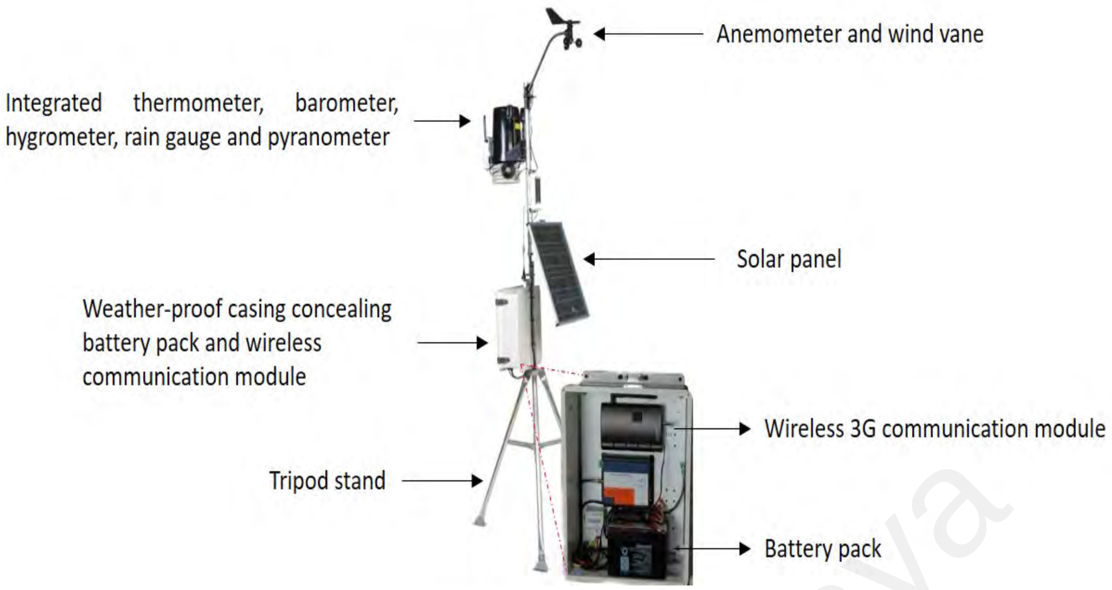


Figure 3.2: Automated weather station

The list of parameters collected by the AWS along with their specifications is presented in Table 3.1.

Table 3.1: **Specifications of sensors in Automated Weather Station**

Parameters	Sensor type	Resolution and units	Range	Accuracy
Air temperature	PN Junction Silicon Diode	1.00°C	-40°C to +65°C	±0.50°C above -7°C
Relative humidity	Film capacitor element	1.00%	1 to 100%	±3% (0 to 90% RH); ±4% (90 to 100% RH)
Wind speed	Wind cups with magnetic switch	0.10 m/s	1 to 80 m/s	± 1 m/s
Wind direction	Wind vane with potentiometer	1°	0 to 360°	±3°
Solar radiation	Silicon photo diode	1.00 W/m^2	0 to 1800 W/m^2	±5%

To ensure accuracy and reliability of data collected by the AWS, calibration of sensors is made twice a year.

3.1.4 Software used in the research

Software is common tools used in research and is distinguished by its function, availability and reliability. The software used in this study is described in the following sub-sections.

3.1.4.1 Map database: Google Earth Pro

Google Earth Pro (Version 7.3.2.5776) is an open-source software that provides access to maps and images of locations around the world. The search for the place of interest can be done using keywords or coordinates. All maps used in this study is extracted using Google Earth Pro.

3.1.4.2 Map database: Open Street Map

Open Street Map (OSM) is an open-source map built by a community of mappers that contribute and maintain data about roads, buildings, and other physical attributes. Contributors use aerial imagery, GPS devices, and low-tech field maps to verify that OSM is accurate and up to date. Points, lines and polygons from OSM are imported into ENVI-MET for accurate mapping of the study area.

3.1.4.3 Spatial mapping software: Geographic Information System

Geographic Information System (GIS) is a software that is commonly used in the geo-spatial mapping. In this study, GIS Version 10.3.1 is used to pre-process maps obtained from Google Earth Pro before it can be used in other software such as ENVI-MET. GIS is also used to define the coverage of the study area.

3.1.4.4 Sample calculation software: OpenEpi

OpenEpi (Version 3.01) is an open-source epidemiologic statistic software for public health which is recommended by the Centre for Disease Control and Prevention for the estimation of sample size. In this study, OpenEpi is used to estimate the minimum number of respondents to achieve adequate sample population.

3.1.4.5 Data analysis software: SPSS

SPSS (Version 25) is a Windows-based program that can be used to perform data entry and analysis. Besides that, SPSS can also be used to generate tables and graphs for data visualization. All statistical evaluation in this study is conducted using this software because it is capable of handling large amounts of data and can perform a wide range of quantitative and qualitative analysis.

3.1.4.6 Thermal comfort indices calculation software: RayMan Pro

The RayMan model is used to assess thermal indices that are derived from the energy balance of the human body (Lin & Matzarakis, 2008; Martinelli et al., 2015; Matzarakis et al., 2010). Meteorological data such as air temperature, air humidity and wind speed are needed as input to quantify thermal bioclimatic conditions (Höppe, 1999; Matzarakis et al., 1999). The short and longwave radiation which are important environmental parameters to derive modern thermal indices can be determined through the RayMan model (Lin et al., 2010). RayMan Pro was used for the assessment of OTC indices such as Predicted Mean Vote (PMV), Physiologically Equivalent Temperature (PET), Standard Effective Temperature (SET*) and Universal Thermal Climate Index (UTCI).

3.1.4.7 Urban microclimate modelling and simulation software: ENVI-MET

ENVI-MET is an open-source software capable of simulating microclimate interactions in an urban environment (Yang et al., 2016; Yang et al., 2016; Yang et al., 2016). The ENVI-MET software (Version 4.4) was used to develop the urban microclimate model of the study area and to simulate urban heat mitigation measures for the improvement of urban microclimate.

3.2 Description of study area: Kuala Lumpur

KL (3º 09’N; 101º 44’E) is the capital city of Malaysia which is one of the fastest-growing cities in the tropical SEA region. KL covers an area of 243 km^2 in the central region of Peninsular Malaysia (Morris et al., 2017) and is located in the centre of GKL that expands over an area of approximate 2,800 km^2 with a density of six million people as reported in the Economic Transformation Program 2010 (Ramakreshnan et al., 2018). Figure 3.3 shows the geographical location of KL in Malaysia.

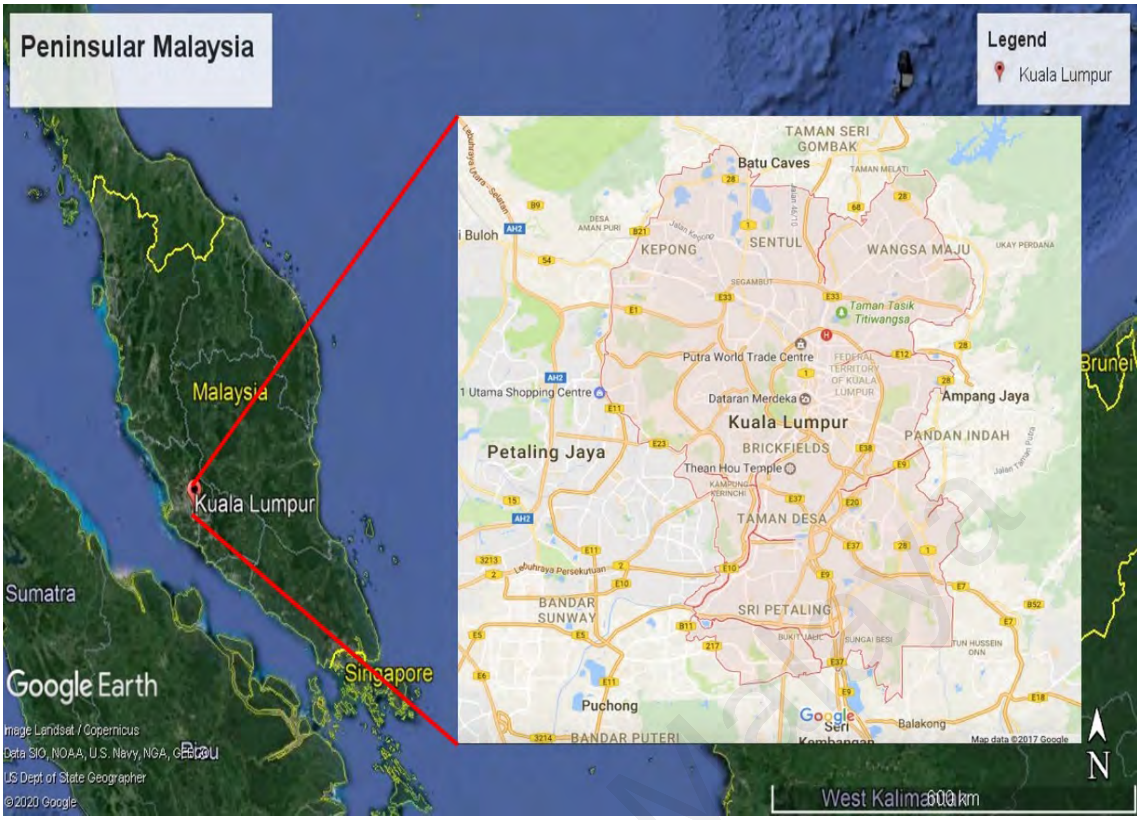


Figure 3.3: The location of Kuala Lumpur (3° 09'N; 101° 44'E)

Source: Google Earth, 2020

KL experiences tropical rainforest climate (*Af*) characterized by annual hot and humid climatic conditions and heavy tropical rains due to its proximity to the Earth's equator (Aflaki et al., 2017). Located 36 m above the sea level, it is characterized by near-uniform monthly mean temperature (26.8-27.0°C) and high mean relative humidity (63-68%) (Morris et al., 2017). KL experiences two main seasons including the wet northeast monsoon (November to March) and the dry southwest monsoon (June to September) with two relatively shorter inter-monsoon periods between the above-mentioned monsoons (Aflaki et al., 2017; Satari et al., 2015). However, KL is presumed to be less affected by the exact intensity of both monsoon winds due to its strategic geographical location in the middle of Sumatra (southwest) and Titiwangsa (northeast) mountain range that provides shielding effect from the prevailing monsoon winds. These unique criteria make the temporal and seasonal UHI assessment in KL, more interesting and vital to be compared with the characteristics of other tropical UHIs. Unfortunately, the existing equipment available under the current research could not provide large spatiotemporal coverage for continuous monitoring of the urban microclimate. Instead, a specific study area was chosen from KL and elaborated in the following section.

3.2.1 Specific study area selection: Masjid Jamek

The study area for the continuous monitoring of urban microclimate is chosen based on the categorization of built types, land cover types and land cover properties as proposed in the local climate zone scheme to ensure consistency in site reporting of the study area for UHI studies (Oke & Stewart, 2012). The heterogeneous properties considered while choosing the study area comprises of different heights of buildings, road networks, human activities, commercial areas and vegetation in the location. For typical microclimate studies, the distance of 100 m is considered appropriate to represent a stable microclimate condition (Chow et al., 2016; Oke, 2004). However, a minimum radius of 200 to 500 m is recommended for the air temperature to adjust to the underlying surface forming an internal boundary layer that does not overlap with neighbouring thermal climate zones (Oke & Stewart, 2012). Hence, the study area chosen covers a radius of 500 m with a total of 0.8 km^2 in area. The chosen study area also fulfils the criteria for local urban studies which expands between 100 m to 1 km (Ibrahim et al., 2017).

The specific study area chosen is Masjid Jamek (MJ) which is located in the city centre of KL. The map showing the MJ study area and landmarks are shown in Figure 3.4. MJ was chosen due to its role as the centre of an economic hub which also has a multifunctional role in commercial, transportation and education aspects. Besides that, MJ is adjacent to Dataran Merdeka which was found to be the hottest (highest ambient temperature of 37°C) among the 75 locations measured in KL city centre (Ibrahim & Samah, 2011).

Besides that, there are additional justifications for selecting this study area. In terms of built-types, the study area represents a heterogeneous built-type that is characterized by high-rise and mid-rise buildings. High-rise buildings in this study area consist of condominiums, residential suites, business suites and office towers, while mid-rise buildings consist of schools, temples, churches, hospitals and commercial lots. Besides that, the land cover type consists of a mixture of dense trees near Kuala Lumpur Eco Forest reserve and scattered trees of bushes and shrubs along the roadsides. On top of that, there are heavy human and traffic activities in this study area especially during the peak hours due to the existence of central bus station at Kota Raya and Mass Rapid Transport (MRT) stations of Pudu Raya and Masjid Jamek interchange stations. There are also several prominent roads passing through this area such as Jalan Tun Perak, Jalan Raja Chulan, Jalan Pudu, Jalan Tun Tan Cheng Lok and Jalan Petaling. With all the factors considered, MJ has deemed a suitable location for the conduct of the proposed research. All research activities from Phase 1 to Phase 3 are conducted in MJ and are elaborated in the following sections.

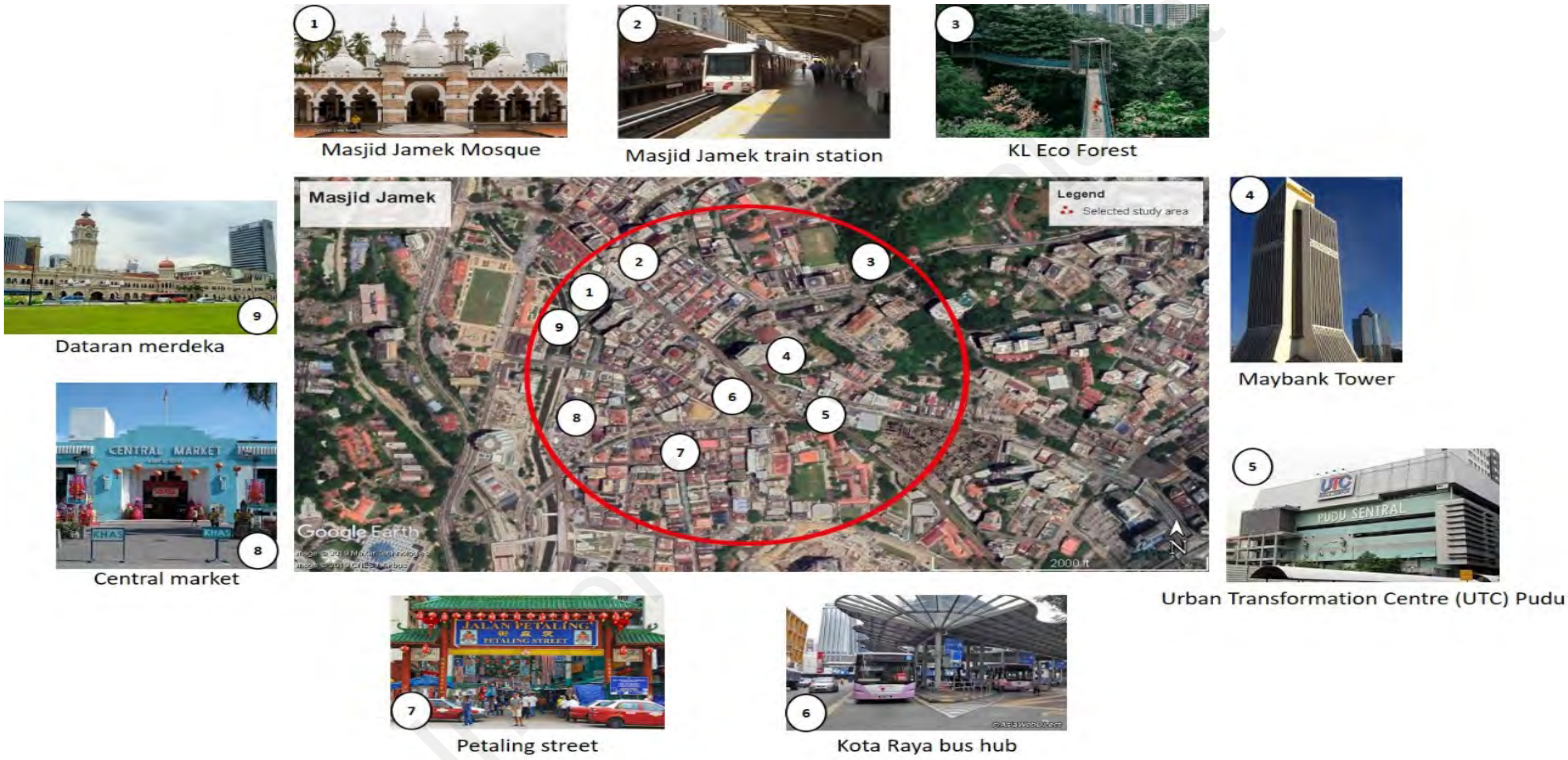


Figure 3.4: The selected study area, Masjid Jamek (3° 8'43.57"N, 101°41'56.59"E)

Source: Google Earth Pro, 2019

3.3 Phase 1: Continuous monitoring of microclimate variations in selected study area

In Phase 1 of the research, the main objective is to monitor the microclimate variations in the study area. The flowchart to achieve RO1 is as shown in Figure 3.5. The following sub-sections are allocated to elaborate the methodological approach used.

Figure 3.5: **Flowchart of continuous monitoring of urban microclimate in study area**

3.3.1 Continuous monitoring of microclimate variations

Meteorological measurements are pre-requisite to any microclimate studies as it defines the thermal environment. After the study area was selected, an AWS is placed in the study area to collect key meteorological data such as air temperature (Ta), relative humidity (RH), wind speed (WS) and direction (WD), and solar radiation (SR). According to Oke (2007), a principle that should be considered while selecting monitoring site is that the diameter of the screen-level sensor should have a radius of about 0.5 km, but this is likely to depend upon the building density (Oke, 2007).

The collected meteorological data are needed to identify the urban microclimate variations in the study area. The data will also be used for the assessment of physiological OTC indices and as an input for the urban microclimate simulation in ENVI-MET software. The data collection is conducted daily at an interval of five minutes at 2 m above ground to record the microclimate variations at human height level. The data collection was conducted for a year from January 2018 to December 2018.

3.3.2 Derivations of meteorological parameters

The AWS deployed in the study area could not provide all the parameters needed for the calculation of indices to determine OTC level. Some parameters need to be estimated based on established formulas and meteorological data collected from the AWS. The derivation formulas for vapour pressure, mean radiant temperature, globe temperature and wet bulb temperature is presented as Appendix A.

3.3.3 Data analyses

3.3.3.1 Variations in urban microclimate

To control the influence of wet days on heat flux and hence, the urban thermal environment, the data from AWS is extracted and pre-processed to only include meteorological parameters from non-rainy days. Descriptive statistics are conducted to identify the mean and standard deviation of the respective meteorological parameters of the study area. The monthly average and the hourly average of microclimate parameters is determined to identify the temporal variations of urban microclimate in the selected study area.

3.3.3.2 Comparison of meteorological data from Malaysian Meteorological Department and Automated Weather Station

A comparison of meteorological data from both AWS and Malaysian Meteorological Department (MetMalaysia) is conducted to identify if the existing meteorological data from the MetMalaysia's principal weather station would be adequate for this current microclimate study. The weather stations belonging to the MetMalaysia consist of simultaneously-operating integrated automated principal weather stations which are designed in compliance with the World Meteorological Organization and the International Civil Aviation Organization standards to fulfil international requirements for weather and climate monitoring.

For this comparison, the meteorological data from the nearest principal weather station at Petaling Jaya (PJ) is chosen to be compared with the data from the AWS placed in the study area. The PJ station (3°6.122'N, 101°38.7092'E) is located approximately 7.5 km to the southwest of the AWS located in the selected study area which is well within MetMalaysia's gridded surface network of a 10 km by 10 km resolution (Osman, 2016). Figure 3.6 shows the location of the principal weather station from the AWS placed in the study area.

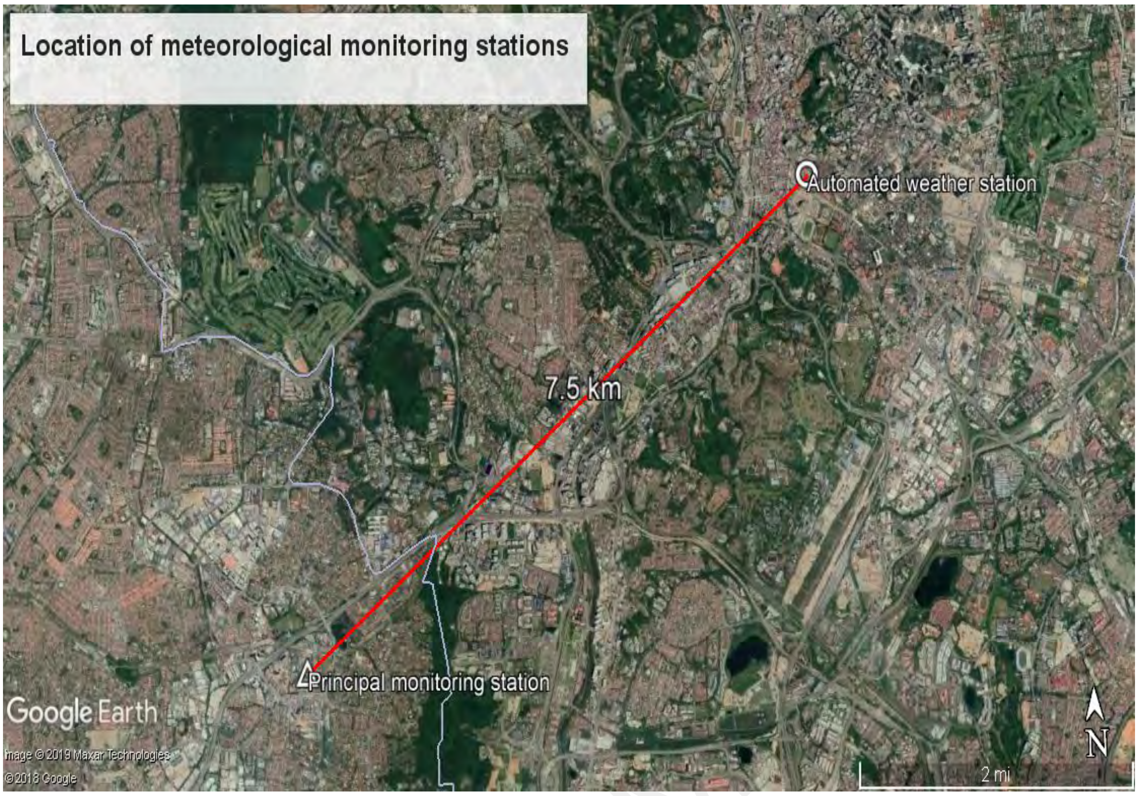


Figure 3.6: Location of MetMalaysia and AWS meteorological monitoring station

A set of meteorological data consisting of Ta, RH, WS and WD, and SR for the year 2018 is requested from MetMalaysia for the principal weather station at PJ (Station ID: 48648). A descriptive analysis is conducted on the meteorological data from both stations. Pearson coefficient correlation analysis is conducted on both sets of data from MetMalaysia and AWS to identify the coherence in data sets. “Exclude cases listwise” was selected in SPSS software to address issues with missing data. Cases in the analysis will only be included for comparison if full meteorological data is available from both AWS and MetMalaysia data sets.

3.4 Phase 2: Evaluation of urban heat towards outdoor thermal comfort and heat-related health implications in study area

In Phase 2 of the research, the main objective is to evaluate and associate urban heat with outdoor thermal comfort and heat-related health implications in the study area. Section 3.4 is allocated to explain the methodology to achieve RO 2 of the research. The flowchart of Phase 2 is summarized as shown in Figure 3.7.

The holistic approach for OTC assessment in a hot-humid tropical region by Fong et al. (2019) and Ng & Cheng (2012) is referred to assess the OTC level of urban communities in the study area. Fanger (1970) suggested any study on thermal stress should explore the six fundamental factors that determine the human thermal environment, such as environmental factors (Ta, Tmrt, RH and WS) and behavioural factors (metabolic rate and clothing) (Epstein & Moran, 2006; Fanger, 1970; Parson, 2003; Vescovi, 2013). Hence, the adaptive steady-state method which evaluates both physiological and psychological OTC was adopted in the study to provide a thorough understanding of OTC level in the study area.

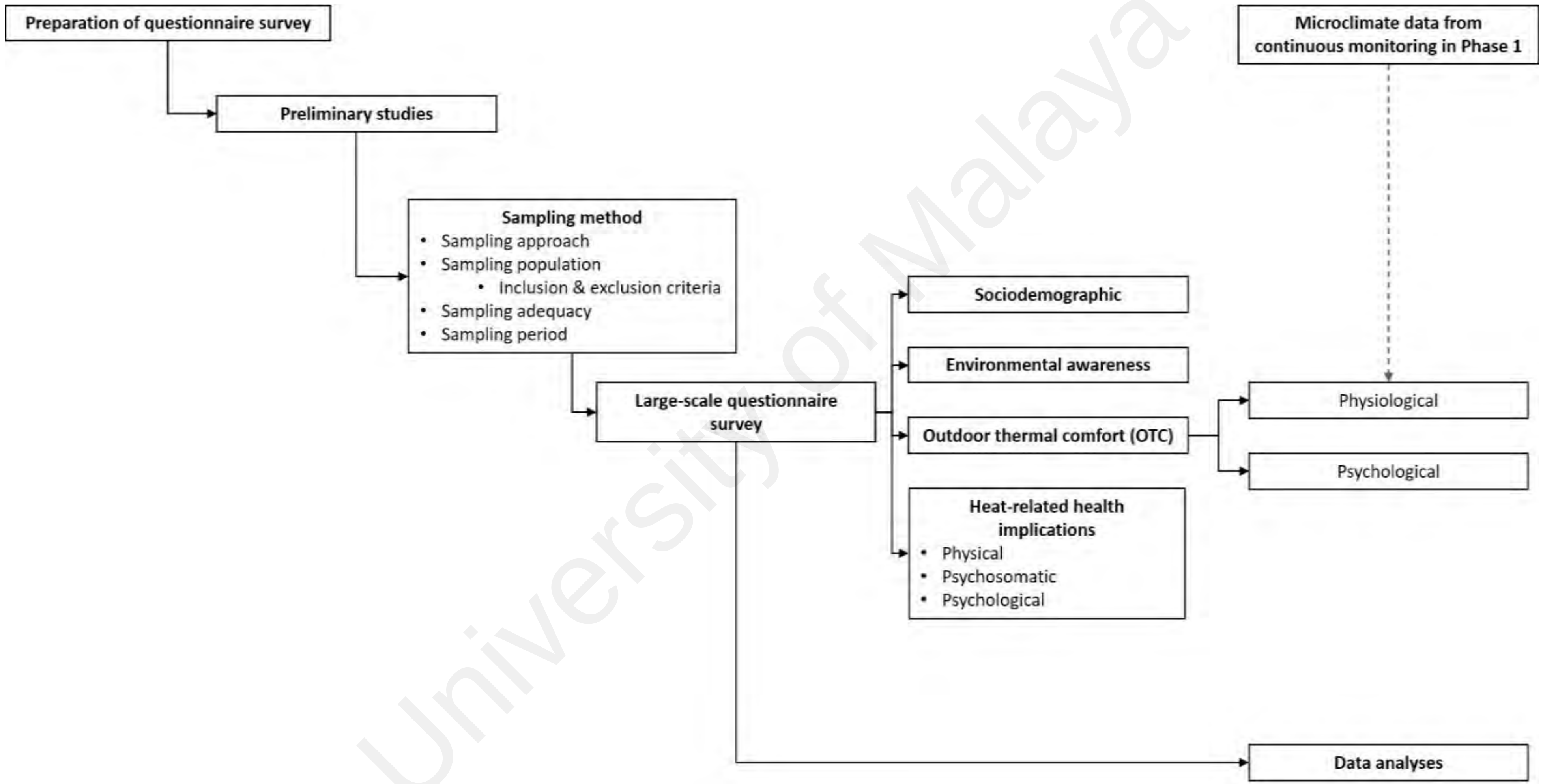


Figure 3.7: **Flowchart of evaluating the impact from urban heat on OTC level and heat-related health implications in study area**

The microclimate data acquired through continuous monitoring in Phase 1 was used to evaluate physiological OTC indices. Meanwhile, a structured questionnaire was used to assess psychological OTC level. The questionnaire has also adopted questions to assess heat-related health implications. Methodology with regards to the structured questionnaire is elaborated in the following section.

3.4.1 Ethical consideration

This study was approved by the University of Malaya Research Ethics Committee (UM.TNC2/UMREC-691). Informed consent was obtained verbally. Respondents were informed that the participation is voluntary and any information obtained from the survey is kept confidential and will only be used for this study. The ethics approval is attached as Appendix B.

3.4.2 A validated structured questionnaire to assess outdoor thermal comfort level and heat-related health implications

An expert-validated structured questionnaire (Appendix C) is disseminated to the target respondents in the study area to assess their psychological OTC level and to identify heat-related health implications. The time of survey is recorded to allow comparison of microclimate variations with physiological OTC indices during data analysis.

An expert-validated structured questionnaire is adopted from Yang et al. (2013) to assess the impact of UHI towards the psychological OTC level. The questionnaire is first prepared in the English language and translated to Bahasa Malaysia (the national language of Malaysia) to facilitate respondents in answering the questionnaire. To assess the impact from urban heat towards the health and well-being of urban communities, a structured questionnaire is fully adopted from Wong et al., (2017) and the Patient Health Questionnaire for Somatic, Anxiety and Depression symptoms (PHQ-SADS) (Wong et al., 2017). The bilingual questionnaire consists of sections which are elaborated as follows:

(a) ***Sociodemographic***

In this section, basic information such as gender, age, nationality, race, education level, occupation, monthly income, and common mode of transport are requested from the respondents. Besides that, respondents are also asked if they live in KL and how often will they be in the city centre of KL in a week. Respondents are also asked about the average duration spent outdoors and the main outdoor activities they usually do in a day.

(b) ***Knowledge of environmental awareness***

This section is dedicated to identifying the level of environmental awareness among the respondents. In this section, the respondents were asked if they noticed any recent changes to the surrounding environment in terms of air temperature, raining and wind pattern, water resources, haze episodes and air quality. The respondents are given the options of “Yes”, “No” and “Don’t know” to answer each question.

(c) ***Outdoor thermal comfort assessment***

In this section, questions are asked regarding the respondent’s heat perception while being exposed to the surrounding thermal environment. The respondents are required to express their thermal sensation, preference, acceptability and comfort levels using established Likert scales such as the Modified ASHRAE seven-point thermal sensation scale and McIntyre thermal preference scale. The Modified ASHRAE scale of “+2” and

“+3” representing “hot” and “very hot” would better define the hot conditions in a tropical climate as compared to “+2” and “+3” representing “warm” and “hot” respectively (Din et al., 2014). The scales used in the assessment of thermal comfort is following ISO 10551: “Ergonomics of The Thermal Environment--Assessment of The Influence of the Thermal Environment Using Subjective Judgement Scales”. The scales used in Chow et al. (2016), Yang et al. (2013) and Din et al. (2014) were also referred to in this study. The scales and rating scores used for OTC assessment in this study are summarized in Table 3.2.

Table 3.2: Summary of scales and rating scores for outdoor thermal comfort study

OTC parameters	Thermal sensation		Thermal acceptance	Thermal preference		Thermal comfort	
Scales and rating scores	-3	Very cool					
	-2	Cold				-2	Very discomfort
	-1	Slightly cool	Acceptable	-1	Warmer	-1	Little discomfort
	0	Neutral	Unacceptable	0	No change	0	No effect
	+1	Slightly warm		1	Cooler	1	Little comfort
	+2	Hot				2	Very comfort
	+3	Very hot					

The thermal sensation is an indication of how the respondent feels towards the thermal environment while being exposed to urban outdoor spaces. The thermal sensation is expressed through a 7-point Likert scale representing a range of cold to hot sensation. The scale is separated by the neutral sensation in the middle to form two equal groups to express the coldness or hotness progressively by using terms such as “slightly” and “very”. The thermal acceptance is a binary response for the respondents to express either the thermal environment is acceptable or unacceptable. The thermal preference is an indication of how the respondents would prefer the thermal environment and are given the options to answer if they wanted a cooler, no change or warmer environment. Lastly, the thermal comfort is to indicate the level of satisfaction being in the thermal environment through a 5-point scale expressing very discomfort levels to very comfortable levels.

(d) ***Heat-related health implications (HRIs)***

In this section, the respondents are required to self-report their physical, psychosomatic and psychological health in response to their heat exposure at urban outdoor spaces. The physical, psychosomatic and psychological symptoms were extracted according to the inventory in PHQ-SADS. Lastly, respondents were asked to express their opinion on whether outdoor thermal discomfort can cause health implications and death, and should it be considered as a public health issue in Malaysia.

3.4.2.2 Preliminary studies: Internal consistency of scales used to identify impact from urban heat on health and well-being of urban communities

From preliminary studies, a reliability analysis was conducted to test the scale's internal consistency. Ideally, the Cronbach alpha coefficient of a scale should be above 0.7 (DeVellis, 2016). The scales used in this study to identify the impact of urban heat on OTC and heat-related health implications of urban communities has good internal consistency with a Cronbach alpha coefficient of 0.926.

3.4.3 Sampling method

The robust sampling approach is important before data collection to ensure the representability of findings from a small population to be generalized towards a larger population. The factors considered in determining sampling method includes sampling approach, sampling population, sampling adequacy and sampling period which is further elaborated in the following sub-sections.

3.4.3.1 Sampling approach

It is recommended that the subjective assessment of OTC needs to be done on-site and instantaneously to fully apprehend the thermal response towards the surrounding thermal environment (Fong et al., 2019). In this study, a clustered random sampling method was used to choose the respondents to answer the structured questionnaire. The selected study area is divided geographically into eight equal areas. Then, three areas were randomly chosen for the conduct of data collection. The questionnaire survey was conducted at locations with similar thermal conditions within the three selected areas. While the data collection involving questionnaire survey was conducted, the microclimate was also concurrently monitored to reflect the urban thermal environment for further analysis. The respondents in the study area are randomly selected to be included in the study according to the criteria as elaborated in the following section 3.4.3.2.

3.4.3.2 Sampling population: Inclusion and exclusion criteria

Only respondents that fulfil the inclusion criteria are invited to answer the questionnaire to ensure the representability of findings. There are several inclusion criteria for the respondents. Firstly, respondents must be urban communities found within the selected study area as the OTC level of a person is directly influenced by surrounding microclimate conditions. Secondly, the respondents are exposed to the outdoor environment for at least 10 to 15 minutes before answering the questionnaire. As people tend to react differently in a diverse thermal environment according to their ability to control or adapt to surroundings, repeated exposure can cause a person to be acclimatized towards a thermal environment. To avoid or minimize the influence of thermal adaptation, the methodology of Kurazumi et al. (2016) is adopted (Kurazumi et al., 2016). The respondents were exposed to the thermal environment for 10 minutes in a standing posture to allow thermal equilibrium between the individual and thermal environment before answering the questionnaire survey. Respondents that do not fulfil the minimum duration of being exposed is persuaded to wait at the outdoor environment for at least 10 minutes before answering the questionnaire. Respondents that do not fulfil the two criteria were automatically excluded for the study. Although there are no age restrictions in this study, respondents that are most likely below 18 years old are avoided because extra consent is needed from their parents or guardians according to the regulations by University of Malaya Research Ethics Committee.

3.4.3.3 Sampling size calculation

Three distinguish approach was used to estimate the minimum number of samples to ensure sampling adequacy. The used of OpenEpi software is from an epidemiological standpoint where prevalence cases of heat-related illnesses (HRI) are used for the sample calculation. The table for sample estimation by Krejcie and Morgan (1970) was referred by estimating the number of population in the selected study area. Lastly, the Cochran formula was used to estimate the number of samples according to the preliminary study conducted in this research. The highest number of samples from the three approach was chosen as the minimum number of samples in this study. The three approaches was undertaken to ensure minimum sampling adequacy for generalization of findings to a bigger population.

In the first approach, OpenEpi was used to estimate the sample size from an epidemiological standpoint. The findings from a similar study by Na et al. (2013) in Korea during summer 2012 was used to estimate the sample size as there are no similar studies in Malaysia that could provide the prevalence to HRI (Na et al., 2013). The values used to calculate sample size in OpenEpi is summarized in Table 3.3. The required total sample size is 206.

Table 3.3: **Input values for sample size calculation in OpenEpi software**

OpenEpi data input	Values
Two-sided significance level (1-alpha)	95
Power (1-beta, % chance of detecting)	80
Ratio of sample size, Unexposed/Exposed	1
Percent of Unexposed with Outcome	7.6
Percent of Exposed with Outcome	23
Odds Ratio	3.5
Risk/Prevalence Ratio	3
Risk/Prevalence difference	15

In the second approach, the table to determine sample size by Krejcie and Morgan (1970) is preferred for sample estimation. As the exact population is unknown for the study area, an estimation has been calculated based on the latest demographic data released by the Department of Statistics, Malaysia (updated on 26 October 2017). As of 2016, the estimated population in KL is 1.79 million over a total area of 243 km^2. Hence, the population density is estimated to be 7,366 per km^2. The selected study area with a radius of 500 m is 0.8 km^2. Thus, the estimated total population in the study area is approximately 6000. According to the sample size determination table for the known population as shown in Table 3.4, the estimated sample size for the study area is 361. However, due to the proximity of sample size for an estimated 1 million populations, this study attempts to collect at least 384 samples from the study area.

Table 3.4: Sample size table for known population

N	S	N	S	N	S
10	10	220	140	1200	291
15	14	230	144	1300	297
20	19	240	148	1400	302
25	24	250	152	1500	306
30	28	260	155	1600	310
35	32	270	159	1700	313
40	36	280	162	1800	317
45	40	290	165	1900	320
50	44	300	169	2000	322
55	48	320	175	2200	327
60	52	340	181	2400	331
65	56	360	186	2600	335
70	59	380	191	2800	338
75	63	400	196	3000	341
80	66	420	201	3500	346
85	70	440	205	4000	351
90	73	460	210	4500	354
95	76	480	214	5000	357
100	80	500	217	6000	361
110	86	550	226	7000	364
120	92	600	234	8000	367
130	97	650	242	9000	368
140	103	700	248	10000	370
150	108	750	254	15000	375
160	113	800	260	20000	377
170	118	850	265	30000	379
180	123	900	269	40000	380
190	127	950	274	50000	381
200	132	1000	278	75000	382
210	136	1100	285	1000000	384

N is population size
S is sample size
Source: (Krejcie & Morgan, 1970)

Lastly, the Cochran formula is used to estimate the minimum sample size for large populations given the desired level of precision and confidence level in the population (Bartlett et al., 2001). As there are very limited OTC studies to serve as the baseline of reference within the urban context of KL, the findings from preliminary study were used instead. From a preliminary study, a total of 489 eligible questionnaires are used to estimate the minimum number of samples with a standard deviation of 1.196 for thermal sensation. As data analysis involves both continuous and categorical data, two Cochran formula was used. The sample size formula for continuous data is expressed as follow:

$$\boldsymbol{n_0 = {t^2 * SD^2}/{e^2}} \qquad \text{(Eq. 2)}$$

Where,

t is the alpha level at one tail;

SD is the standard deviation;

e is the margin of error.

The margin of error is calculated based on the following formula:

$$\boldsymbol{e = Critical\,Value * Standard\ Error} \qquad \text{(Eq. 3)}$$

Where,

The critical value for a confidence interval of 99% is 2.58.

The standard error is calculated based on the following formula:

$$\boldsymbol{Standard\ Error} = {}^{\boldsymbol{SD}}\!/\!_{\boldsymbol{\sqrt{n}}} \qquad \text{(Eq. 4)}$$

Where,

n is the number of sample from preliminary study.

The sample size estimation for continuous data is 490. On the other hand, the sample size formula for categorical data is expressed as follow:

$$\boldsymbol{n_0} = {}^{\boldsymbol{t^2pq}}\!/\!_{\boldsymbol{e^2}} \qquad \text{(Eq. 5)}$$

Where,

p is the proportion of population which has the attribute of interest;

q is 1-p;

p is set to 0.5 to produce the maximum possible sample size. The sample size estimation for categorical data is 86.

In summary, the minimum sample number calculated using OpenEpi software, Krejcie and Morgan (1970) sample size table and Cochran's formula is 206, 384, 490 and 86 respectively. Hence, 490 was chosen as the minimum required samples for the data collection to ensure sampling adequacy.

3.4.3.4 Sampling period

Heat fluxes are found to be significantly influenced by precipitation (Niu et al., 2016; Ramakreshnan et al., 2019). Hence, the time frame of data collection is carefully chosen to avoid rainy days as they will influence the surrounding thermal environment and subsequently the OTC level. Weather forecast from the MetMalaysia is referred in advance so that data collection can be conducted on clear and non-rainy days.

The variations in UHII in KL was found to vary between 0800 to 2000 (Ramakreshnan et al., 2019). The diurnal manner of UHII formation in KL is shown in Figure 3.8.

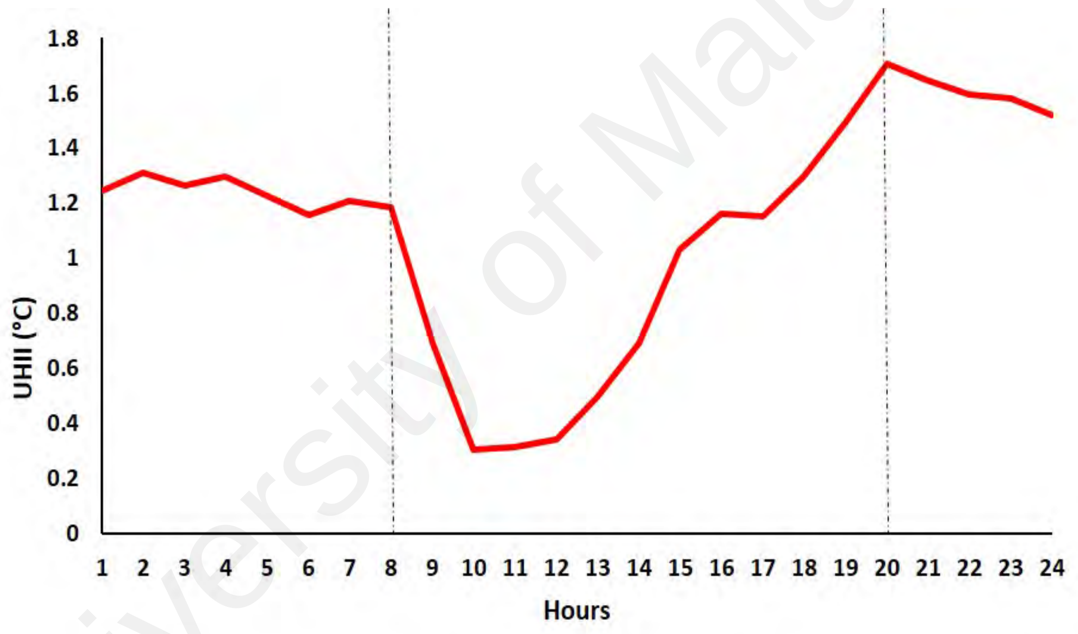


Figure 3.8: Diurnal variation of urban heat island intensity

To address the variations of microclimatic conditions within a day, the period for data collection was set for twelve hours from 0800 to 2000 following the UHII variations in KL. The assessment of physiological OTC is elaborated in the following section.

3.4.4 Assessing the physiological outdoor thermal comfort level through thermal comfort indices

Unlike psychological OTC and HRIs which can be evaluated via the questionnaire survey, the physiological OTC can only be evaluated through thermal comfort indices. The meteorological data collected from the continuous monitoring of urban microclimate in Phase 1 is used to evaluate the physiological OTC indices. A total of 5 thermal comfort indices were chosen to express the physiological OTC level of the respondents. The indices shown in Table 3.5 were chosen as they are frequently used to evaluate thermal environmental stress or thermo-physiological strain.

Table 3.5: **List of thermal comfort indices chosen for the study**

Thermal comfort indices	Abbreviations
Physiological Equivalent Temperature	PET
Predicted Mean Vote	PMV
Standard Effective Temperature	SET*
Universal Thermal Climate Index	UTCI
Wet-Bulb Globe Temperature	WBGT

The chosen OTC indices are further elaborated in the following sub-section.

3.4.4.1 Physiological Equivalent Temperature

PET is the air temperature where the heat balance of the human body is balanced between two human body nodes (core and skin) under typical indoor settings equals to the complex outdoor conditions being assessed (Koerniawan & Gao, 2014b, 2014a, 2015; Makaremi et al., 2012; Nasir et al., 2012; Qaid et al., 2016). Data on Ta, RH or vapour pressure, WS, mean radiant temperature (Tmrt), human clothing and activity level is needed for the estimation of PET using the RayMan model. The findings from a study conducted in Singapore (which is also a tropical city) is referred to in determining the clothing value and metabolic rate. The average clothing value is assumed to be 0.30 clo (1 clo = 0.155°C) while the metabolic rate was assumed to be 1.4 met for standing (1 met=58.15 W/m^2) (Yang et al., 2013).

3.4.4.2 Predicted Mean Vote

According to ISO 7730:2005 "Ergonomics of The Thermal Environment – Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the Predicted Mean Vote (PMV) and Predicted percentage dissatisfied (PPD) Indices and Local Thermal Comfort Criteria", PMV predicts the mean value of thermal sensation votes (TSV) of a large group of people being exposed to the same thermal environment according to the 7-point scale as shown in Table 3.6. Thermal balance is achieved when internal heat production within the body is equal to the loss of heat to the environment through human thermoregulatory response such as sweating to maintain heat balance.

Table 3.6: **7-point thermal sensation scale**

Scoring value	Thermal sensation vote
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

The PMV can be estimated for different combinations of metabolic rate, clothing insulation, air temperature, mean radiant temperature, air velocity and humidity. The equation that expresses PMV is shown below:

$$\boldsymbol{PMV} = [\boldsymbol{0.303}^{(-\boldsymbol{0.036M})} + \boldsymbol{0.028}] * \{(\boldsymbol{M} - \boldsymbol{W}) - \boldsymbol{3.05}^{-\boldsymbol{3}} * [\boldsymbol{5733} - \boldsymbol{6.99} * (\boldsymbol{M} - \boldsymbol{W}) - \boldsymbol{p_a}] - \boldsymbol{0.42} * [(\boldsymbol{M} - \boldsymbol{W}) - \boldsymbol{58.15}] - \boldsymbol{1.7}^{-\boldsymbol{5}} * \boldsymbol{M} * (\boldsymbol{5867} - \boldsymbol{p_a}) - \boldsymbol{0.0014} * \boldsymbol{M} * (\boldsymbol{34} - \boldsymbol{T_a}) - \boldsymbol{3.96}^{-\boldsymbol{8}} * \boldsymbol{f_{cl}} * [(\boldsymbol{t_{cl}} + \boldsymbol{273})^{\boldsymbol{4}} - (\boldsymbol{T_{mrt}} + \boldsymbol{273})^{\boldsymbol{4}}] - \boldsymbol{f_{cl}} * \boldsymbol{h_c} * (\boldsymbol{t_{cl}} - \boldsymbol{T_a})\} \quad \text{(Eq. 6)}$$

Where,

M is the metabolic rate in W/m^2;

W is the effective mechanical power in W/m^2;

p_a is the water vapour partial pressure in Pascal;

T_a is the air temperature in °C;

f_{cl} is the clothing surface area factor;

t_{cl} is the clothing surface temperature in °C;

Tmrt is the mean radiant temperature in °C;

h_c is the convective heat transfer coefficient in W/m^2*K.

(a) ***Predicted percentage dissatisfied***

PPD is an index commonly associated with PMV which is used to predict the number of people likely to feel uncomfortably warm or cool. PPD predicts the number of thermally dissatisfied persons according to the following equation:

$$\boldsymbol{PPD} = \boldsymbol{100} - \boldsymbol{95}^{-\boldsymbol{0.03353} * \boldsymbol{PMV}^{\boldsymbol{4}} - \boldsymbol{0.2179} * \boldsymbol{PMV}^{\boldsymbol{2}}} \quad \text{(Eq. 7)}$$

Thermally satisfied people are those that voted their thermal sensation to be between -1 (slightly cool) to 1 (slightly warm) while those that voted otherwise are considered as thermally dissatisfied. The association of PPD with PMV is presented in Figure 3.9.

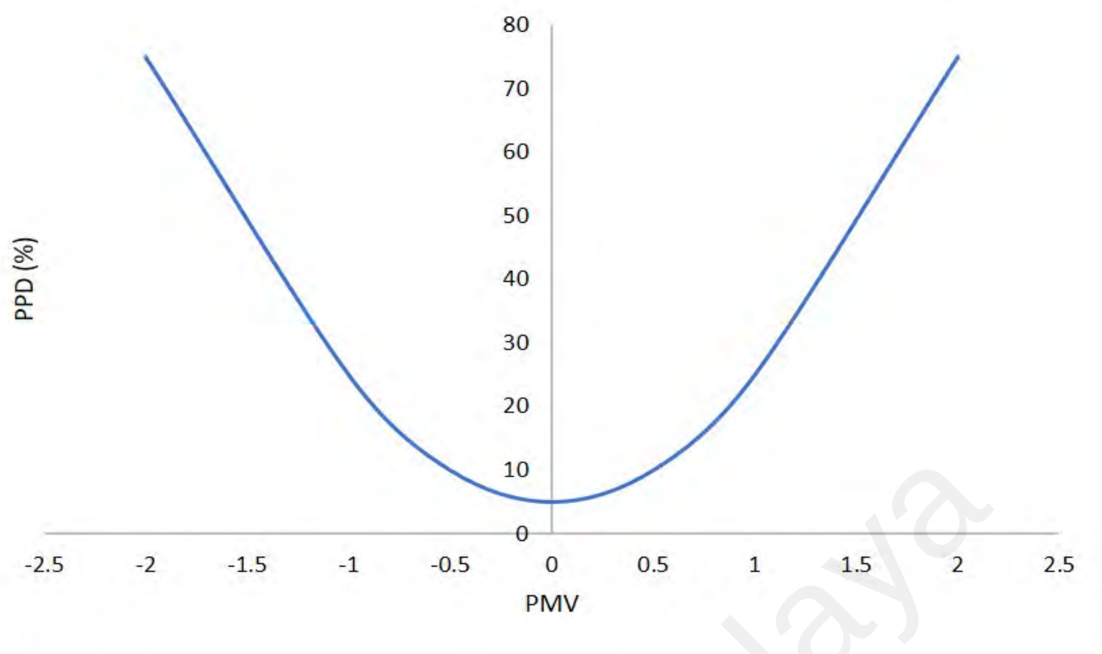


Figure 3.9: PPD as a function of PMV

3.4.4.3 Standard Effective Temperature

SET* is the air temperature of a hypothetical environment at 50% RH with the assumption that the occupants are wearing standard clothing for the given activity in the real environment with wind speed less than 0.1 m/s and the mean radiant temperature equals the air temperature (ANSI/ASHRAE 55, 2013). The programming code for the calculation of SET* using JavaScript in SI units is presented in ANSI/ASHRAE Standard 55-2017: Thermal Environmental Conditions for Human Occupancy.

3.4.4.4 Universal Thermal Climate Index

UTCI is defined as the equivalent ambient temperature of a reference environment that causes the same physiological response of a reference person as the actual environment would imply (Blazejczyk et al., 2012; Hanipah et al., 2016). Due to the high complexity, and thus high computational effort, UTCI can only be approximated using a regression formula (Jendritzky et al., 2012). A subroutine UTCI_approx was written to calculate UTCI values approximated by a 6th order polynomial from the meteorological data input of air temperature (-50 to +50 °C), mean radiant temperature (30°C below to 70°C above air temperature), wind speed in 10 m (0.5 to 17 m/s) and water vapour pressure in hPa (below 50 hPa or 100% relative humidity). The UTCI program code can be obtained from http://www.utci.org/utci_doku.php.

3.4.4.5 Wet-Bulb Globe Temperature

WBGT is a thermo-physiological index that is widely used to measure an individual's heat stress under direct sunlight. WBGT is calculated based on air and globe temperatures, relative humidity, wind speed, sun azimuth angle and insolation in which the coefficients have been determined empirically (Chow et al., 2016). The equation for the calculation of WBGT directly from Kestrel 4400 (an instrument used for measuring heat stress) is as follow:

$$\boldsymbol{WBGT = 0.7T_{wb} + 0.2T_g + 0.1T_a} \qquad \text{(Eq. 8)}$$

Where,

T_{wb} is wet-bulb temperature in °C;

T_g is globe temperature in °C;

T_a is air temperature in °C

3.4.5 Data analyses

For all data analyses, the option “Exclude cases listwise” was selected in SPSS software to address issues with missing data. Cases will only be included for analysis if the full data set is available.

3.4.5.1 Sociodemographic profile of urban communities

The demographic of the respondents were analysed using SPSS software. In general, the mean and standard deviation of the information acquired was identified to provide an overview of the respondents chosen for the study.

3.4.5.2 Evaluation of physiological outdoor thermal comfort level

The meteorological parameters that coincide with the time of the survey are identified and used to evaluate physiological OTC indices. The heat stress classes of each index were identified to express physiological heat strain in the study area. A Pearson correlation analysis is conducted to identify the coherence among OTC indices. The OTC indices with the highest coherence will be selected to represent physiological OTC to be compared with the findings from psychological OTC.

3.4.5.3 Evaluation of psychological outdoor thermal comfort level

The frequency and percentage distribution of votes for thermal sensation, acceptance, preference and comfort levels were determined to assess the psychological OTC level of the urban communities.

3.4.5.4 Temporal variations in outdoor thermal comfort level

(a) Diurnal variations in outdoor thermal comfort level

The mean of thermal sensation, acceptance, preference and comfort levels are evaluated and plotted against hours in a day to show diurnal variations in psychological OTC level.

(b) The influence of duration of urban heat exposure on thermal comfort level

The duration of exposure was compared to the mean of thermal sensation votes (MTSV) to identify if there are significant influence in duration of exposure towards the MTSV. A Kruskal-Wallis H test was conducted for comparison involving more than two groups.

3.4.5.5 Coherence in physiological and psychological outdoor thermal comfort level

A correlation analysis is conducted to identify the coherence of physiological and psychological OTC level. The level of coherence will be an indicator if microclimate variables are adequate to explain the variance in OTC level at urban outdoor spaces.

3.4.5.6 Expressing psychological outdoor thermal comfort via physiological equivalent temperature

(a) Identifying the neutral temperature of the urban community in study area

Neutral temperature is the temperature where respondents are expected to feel neutral, i.e., mean of thermal sensation votes (MTSV) equals 0, under the combination of meteorological parameters as expressed through the physiological OTC indices. The selected OTC indices are divided into bins with an increment of 0.5°C each. Then, the

MTSV is identified and weighted with the number of responses in the corresponding bin to remove the effect of large randomness from small sample size bins. Linear regression is performed to identify the neutral temperature by plotting the (MTSV) against the selected OTC indices.

(b) ***Identifying the acceptable temperature range of the urban community in study area***

The line of thermal acceptance is expected to follow a second-degree polynomial function. Hence, to identify the acceptable temperature range of the urban community in the study area, the probability of the urban community not accepting the thermal environment is plotted against the selected OTC indices. The intersection line of y=0.3 was chosen to identify the acceptable range of temperature for at least 70% of the population in the study area.

(c) ***Identifying the preferred temperature of the urban community in study area***

Probit analysis is conducted to identify the preferred temperature of the urban community in the study area. The preferred temperature is identified as the temperature where individuals do not prefer either a cooler or warmer thermal environment. Each thermal preference is represented by a log-linear function representing the preference of a cooler and warmer temperature. The intersection would indicate the preferred temperature.

(d) ***The temperature to express thermal comfort in study area***

The mean of thermal comfort votes (MTCV) is identified and plotted against the selected OTC indices to identify the temperature where the urban community would attain thermal comfort. The intersection at MTCV equals 0 of the linear regression would determine the temperature for an individual to report thermal comfort or discomfort in the study area.

3.4.5.7 A heat-stress guideline

By comparing the findings from neutral temperature, preferred temperature, acceptable temperature range and cut-off point of thermal comfort/discomfort, a heat stress guideline is proposed for a tropical city. The proposed heat-stress guideline adopted the modified ASHRAE scale used in the validated questionnaire. The neutral temperature will serve as the mid-point to express thermal sensation in the heat stress guideline. The temperature ranges for "slightly warm", "hot" and "very hot" are obtained by a subsequent increase of 4°C PET from the neutral temperature while, the temperature ranges for "slightly cool", "cold" and "very cold" is obtained through a subsequent reduction of 4°C PET from the neutral temperature (Lin & Matzarakis, 2008).

3.4.5.8 Identifying the prevalence of heat-related health implications due to urban heat exposure in a tropical city

The frequency and percentage distribution of the physical, psychosomatic and psychological symptoms due to urban heat exposure is determined. This is to identify the prevalence of common heat-related symptoms experienced by the urban communities exposed to urban heat in a tropical city.

3.4.5.9 Evaluating health impact scores for physical, psychosomatic and psychological health impact

To identify the prevalence of health symptoms by physical, psychosomatic and psychological health, health impact scores are adopted from validated health screening tools. This is to allow the identification of the severity of health impact as a result of urban heat exposure. The health impact scores for physical, psychosomatic and psychological health symptoms are elaborated as follows.

(a) ***Physical health impact scores***

To identify the prevalence of physical health symptoms, each item under the physical health questionnaire are calculated (1 score for "Yes" and 0 scores for "No" and "Don't know") for each respondent to identify their physical health impact score. The scoring and its respective category are presented in Table 3.7.

Table 3.7: Physical health impact scoring category

Physical Health Impact Score	Category
0 – 4	Low
5 – 9	High

The physical health impact score is expressed in a dichotomous manner with scores 0 to 4 for low physical impact and scores 5 to 9 for high physical impact.

(b) ***Psychosomatic health impact scores***

Patient health questionnaire 15 (PHQ-15) is a validated screening tool to screen for the severity of psychosomatic symptoms among the urban communities in the study area. Originally, the PHQ-15 scores consist of four levels of psychosomatic symptom severity categorized as minimal (0 to 4), low (5 to 9), moderate (10 to 14), and high (15 to 30) (Kroenke et al., 2010). In this study, the psychosomatic symptom scores were clustered into low severity and high severity. Table 3.8 summarizes the two groups of psychosomatic severity with their respective scores that range from 0 to 30. A higher value of the PHQ-15 score indicates a higher severity of psychosomatic symptoms.

Table 3.8: PHQ-15 score

PHQ-15 Score	Somatic Severity	Group
0 – 4	Minimal	Low
5 – 9	Low	
10 – 14	Moderate	High
15 – 30	Severe	

(c) ***Psychological health impact scores***

Under psychological health impact, the categories are further distinguished according to anxiety health impact and depression health impact. The health impact score for anxiety and depression is elaborated as follows.

i *Anxiety health impact score*

The anxiety health impact score which is based on General Anxiety Disorder (GAD) -7 score is a validated screening tool to screen for anxiety severity among the urban communities in the study area. The GAD-7 score consists of four levels of anxiety severity categorized as non-minimal (0 to 4), mild (5 to 9), moderate (10 to 14) and severe (15 to 21) (Spitzer et al., 2006). In this study, the anxiety health impact scores were clustered into low severity and high severity. Table 3.9 summarizes the two groups of anxiety severity with their respective scores that range from 0 to 21. A higher value of the GAD-7 score indicates a higher severity of anxiety symptoms.

Table 3.9: GAD-7 anxiety health impact score

GAD-7 Score	Anxiety severity	Group
0 – 4	None-minimal	Low
5 – 9	Mild	
10 – 14	Moderate	High
15 – 21	Severe	

ii *Depression health impact score*

The patient health questionnaire 9 (PHQ-9) is a validated screening tool used to screen for the severity of depression (Kroenke & Spitzer, 2002) among the urban communities in the study area. The scoring of PHQ-9 consists of four levels of depression severity categorized as non-minimal (0 to 4), mild (5 to 9), moderate (10 to 14), moderately severe (15 to 19) and severe (20 to 27) (Kroenke et al., 2010). In this study, the depression severity scores were clustered into 0 to 9 for low severity and 10 to 27 for high severity. Table 3.10 summarizes the two groups of depression severity with their respective scores. A higher score for the PHQ-9 indicates a higher severity of depression symptoms.

Table 3.10: PHQ-9 depression health impact score

PHQ-9 Score	Depression Severity	Group
0 – 4	None-minimal	Low
5 – 9	Mild	
10 – 14	Moderate	High
15 – 19	Moderately Severe	
20 – 27	Severe	

3.4.5.10 The association of selected sociodemographic factors influencing the outcome of physical, psychosomatic and psychological health symptoms

In subsequent data analysis, the association of HRIs with selected sociodemographic factors were identified. A univariate/multivariate analysis was conducted for the health impact scores of physical, psychosomatic and psychological symptoms with selected sociodemographic indicators such as gender, age group, ethnicity and duration of outdoor exposure in a day.

3.4.5.11 Factorial analysis of physical, psychosomatic and psychological health symptoms

In total, there are 38 health symptoms included in this study. Through Exploratory Factor Analysis (EFA), all heat-related health implications according to physical, psychosomatic and psychological symptoms are loaded into components which were then further classified as specific clustered symptoms.

3.4.5.12 The association of clustered symptoms with outdoor thermal comfort level

The association of OTC with each clustered symptom were performed to identify the influence of sociodemographic indicators as confounding factors. A Kolmogorov Smirnov test is conducted to test for normality within the clustered symptoms. The data analysis is continued with the Mann-Whitney U test for comparison involving two groups while the Kruskal-Wallis H test is used for comparison involving more than two groups.

3.5 Phase 3: Developing and validating the 3D urban microclimate model of study area

In Phase 3 of the research, there are two main objectives. Firstly, is to develop and validate a 3D urban microclimate model (UMM) of the study area. Section 3.5 is allocated to explain the methodology to achieve RO 3 of the research. Meanwhile, the second objective of Phase 3 is elaborated in Section 3.6. The flowchart in developing and validating the 3D UMM is shown in Figure 3.10.

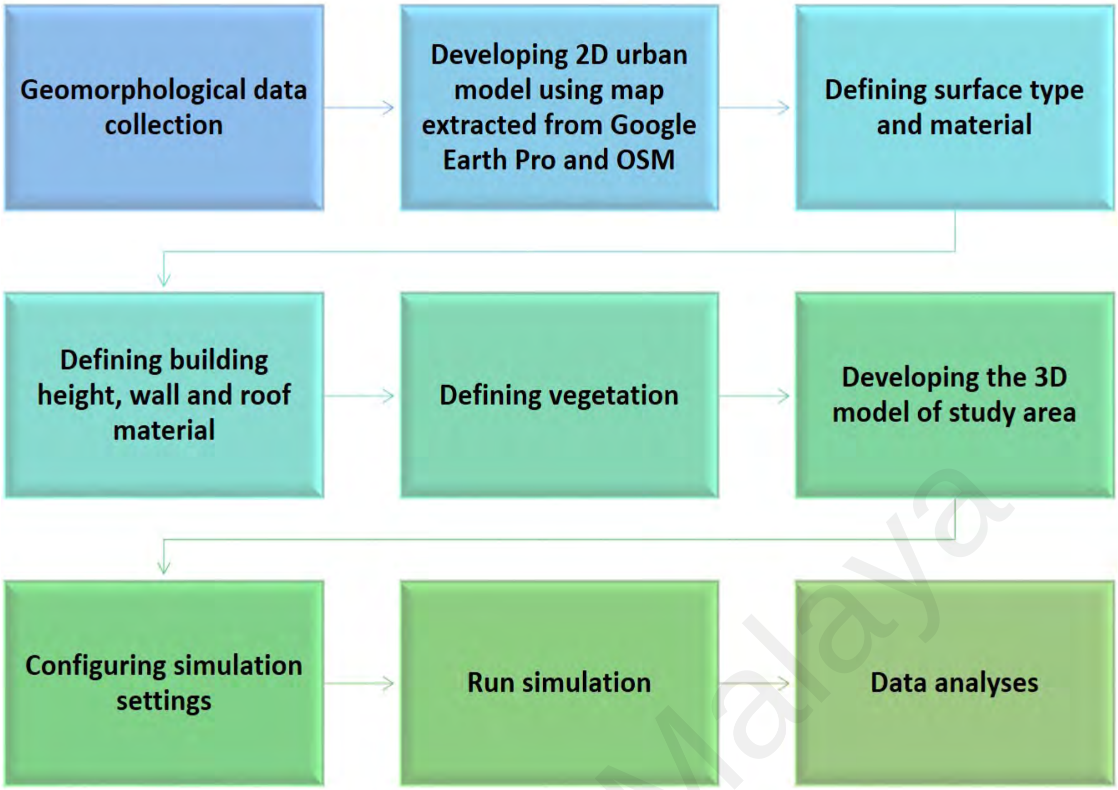


Figure 3.10: **Flowchart in developing and validating the 3D urban microclimate model of study area**

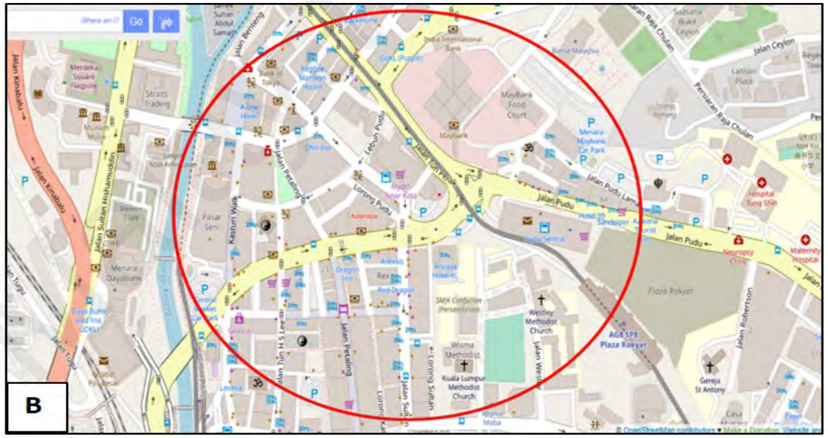
3.5.1 Geomorphological data collection

Fieldworks are conducted to collect geomorphological data within the selected study area. Ground measurements were carried out to gather information such as building height, surface type, land use type, vegetation and other relevant data for precise modelling of the UMM. The methodology to develop UMM of the study area is elaborated in the next section.

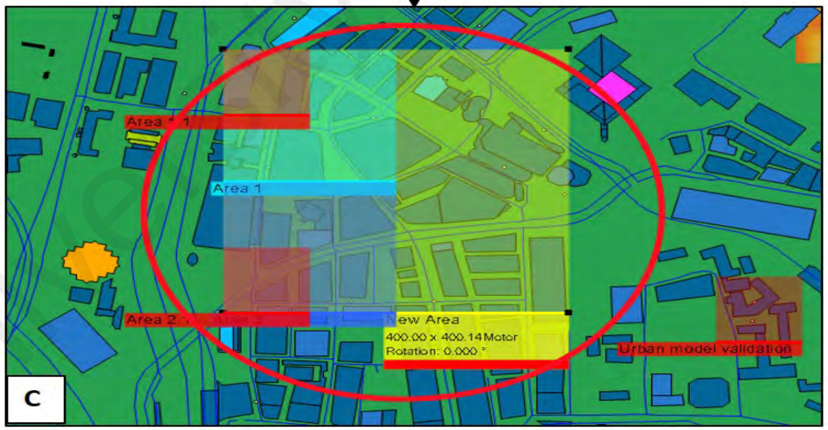
3.5.2 Developing the urban microclimate model of study area in ENVI-MET

The UMM of the selected study area was developed via the ENVI-MET software. The process of UMM development is summarized in Figure 3.11. The detailed methodology of developing the UMM is further elaborated in the following sub-sections.

Study area in Google Earth Pro



Geomorphological information in Open Street Map



The urban model developed in ENVI-MET software

Figure 3.11: Summary of urban microclimate model development in ENVI-MET software

3.5.2.1 Importing geomorphological information into ENVI-MET

The geomorphological information such as points, lines and polygons that define the buildings in the study area is extracted from OSM as a template to build the 2D layer in ENVI-MET software. Through a feature in the ENVI-MET software named ENVI-MET Monde, the geomorphological information from OSM can be imported directly into the software. Google Earth Pro is referred to check if there is missing information from OSM. The base map of the selected study area extracted from OSM is shown in Figure 3.12.

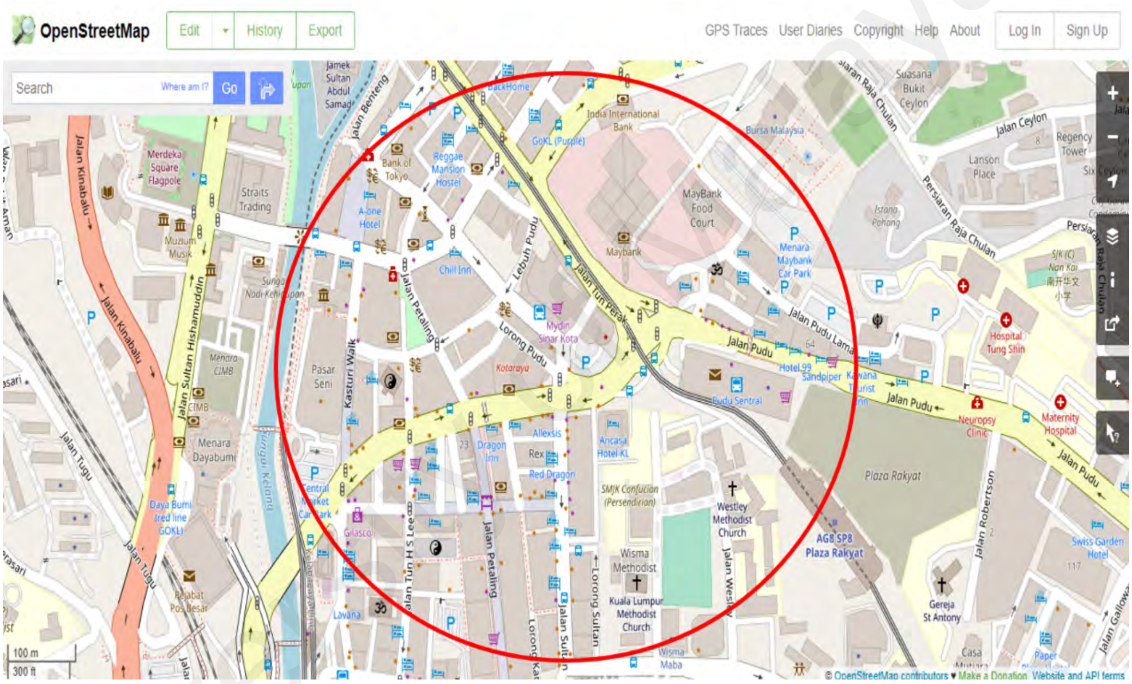


Figure 3.12: **Base map of selected study area extracted from Open Street Map**

The model when imported into ENVI-MET will exist in the ENVI-MET World as shown in Figure 3.13.

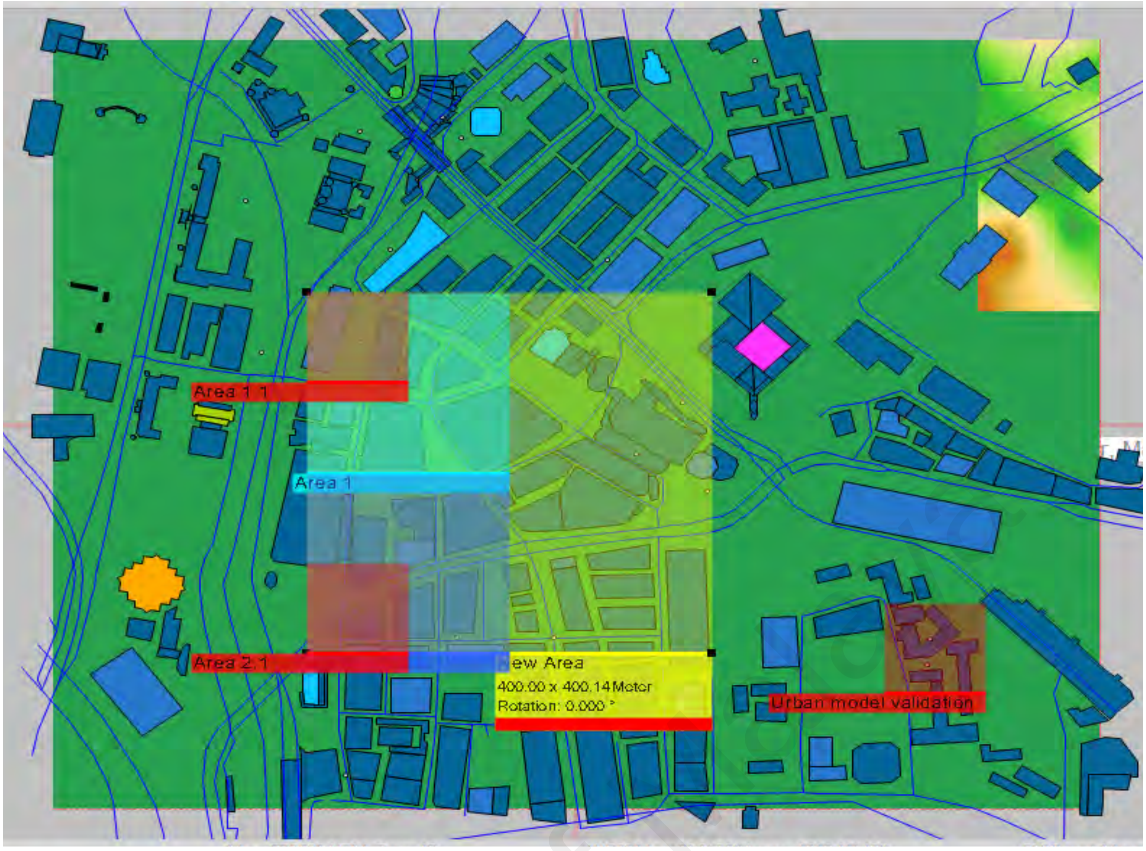


Figure 3.13: **The World in ENVI-MET Monde**

The area has been rendered with a 200 x 200 x 25 (x-y-z) grids. The length (dx), width (dy) and height (dz) of each grid represent 5 m respectively. The resolution chosen is well within the suitable range of ENVI-MET software, i.e., 0.5 m to 10 m. On top of that, the resolution is a reasonable compromise between accuracy and computation time. Five nesting grids were allocated to the model edges to allow a more stable and accurate simulation.

3.5.2.2 Defining attributes in the urban microclimate model

After importing geomorphological information of the study area into ENVI-MET Monde, various attributes such as surface type and material, building height and material, and vegetation was defined. The datasheet for wall and roof material is summarized in Table 3.11.

Table 3.11: **Datasheet of wall and roof material in urban microclimate model**

Parameter	Value
Name	Default Wall – moderate insulation
Database-ID	000000
Colour	Grey
Roughness Length	0.02
Wall thickness (Outer layer, Centre layer, Inner layer)	0.01, 0.12, 0.18
Usage	Wall or Roof

Meanwhile, the roughness length, albedo and emissivity of the pavement materials and soil surface is presented in Table 3.12 and Table 3.13, respectively.

Table 3.12: **Datasheet of existing pavement material in urban microclimate model**

Parameter	Value
Name	Concrete Pavement Grey
Database-ID	0100PG
Colour	White
z0 Roughness Length	0.01
Albedo	0.50
Emissivity	0.90

Table 3.13: **Datasheet of loamy soil in urban microclimate model**

Parameter	Value
Name	Loamy Soil
Database-ID	0100LO
Colour	Light brown
z0 Roughness Length	0.02
Albedo	0.00
Emissivity	0.98

Receptors are added to the study area to extract point-specific microclimate data. Next, the UMM is exported as an area input file (.INX) file for simulation and data analyses.

3.5.3 Configuring urban microclimate simulation file

3.5.3.1 Initiating the urban microclimate simulation

Before initiating microclimate simulation, the meteorological data input from the continuous monitoring in Phase 1 of the study was used to configure the simulation file to replicate the actual environmental conditions in the study area. The wind speed at 10 m height is extrapolated using the power law (Manwell et al., 2010) as shown in Eq. (9).

$$\boldsymbol{v_2 = v_1 (\frac{z_2}{z_1})^{\propto}} \quad \text{(Eq. 9)}$$

Where,

V_1 is velocity at height Z_1;

V_2 is Velocity at height Z_2;

Z_1 = Height 1 (lower height);

Z_2 = Height 2 (upper height); and

α = wind shear exponent

The wind direction is identified from the average wind direction observed in the study area. The roughness length was estimated according to the European Wind Atlas (Petersen & Troen, 2020). The value 0.4 was chosen because the landscape in the study area contains rough and uneven terrains. The initial meteorological conditions for the simulation model is summarized in Table 3.14.

Table 3.14: Initial meteorological conditions for microclimate simulation

Parameters	Value
Wind	
Wind speed measured in 10 m height (m/s)	2.32
Wind direction (°)	123
Roughness length at measurement site	0.4

The simulation of the urban microclimate variation in the selected study area was conducted for 24 hours with simple radiative forcing applied for Ta and RH. The simple radiative forcing applied to the Ta and RH is shown in Table 3.15.

Table 3.15: Simple radiative forcing of air temperature and relative humidity in the microclimate model

Hours	Ta (°C)	RH (%)
1	27.55	76.43
2	27.24	77.56
3	26.94	78.37
4	26.70	79.11
5	26.49	79.77
6	26.26	80.4
7	26.12	80.39
8	26.48	78.85
9	27.78	72.82
10	29.15	66.19
11	30.34	60.02
12	31.27	55.52
13	32.05	52.49
14	32.53	50.71
15	32.73	50.13
16	32.66	50.96
17	32.01	52.03
18	31.57	55.54
19	30.75	59.30
20	30.00	63.47
21	29.50	66.09
22	29.09	68.33
23	28.76	70.05
24	28.44	71.34

3.5.4 Data analyses

3.5.4.1 Validation of urban microclimate model of study area

In the validation process, the simulated results from ENVI-MET is compared with the microclimate data from AWS. The resemblance of both sets of data will determine the reproducibility and reliability of ENVI-MET in simulating actual urban microclimate variations. Salata et al. (2016) suggested that the reliability of ENVI-MET in predicting Ta and Tmrt needs to be testified (Salata et al., 2016). However, in this study, the reliability of Tmrt couldn't be testified as the AWS placed in the study area is not directly measuring this parameter. Rather, Tmrt is estimated from Equation (1) based on Sen & Nag (2019) using meteorological data from AWS. Hence, on top of Ta, the RH and WS are also testified to ensure the reliability of ENVI-MET for microclimate simulation in this research.

Two validation measures were conducted to investigate the capability of the UMM to predict microclimate variations. In particular, two sets of microclimate data were used to test the accuracy of the UMM in simulating actual microclimate variations. Firstly, the comparison is made between the yearly data of microclimate observation from AWS and the simulated microclimate data from ENVI-MET. The findings from this comparison would show the ability of ENVI-MET in comprehensively reproducing actual microclimate variations. Secondly, to test if ENVI-MET would be able to simulate accurate daily microclimate variations, the validation is repeated by comparing observed microclimate data for selected days with the simulated microclimate data from ENVI-MET.

3.6 Phase 3: Exploring the potential of urban heat mitigation measures through microclimate simulation model

In Phase 3 of the research, the second objective is to simulate and recommend urban heat mitigation measures for the improvements of urban microclimate in the study area. Section 3.6 is allocated to explain the methodology to achieve RO 4 of the proposed research. The UMM developed and validated from Section 3.5 is used for the simulation work in Section 3.6. The flowchart to achieve RO 4 is presented in Figure 3.14.

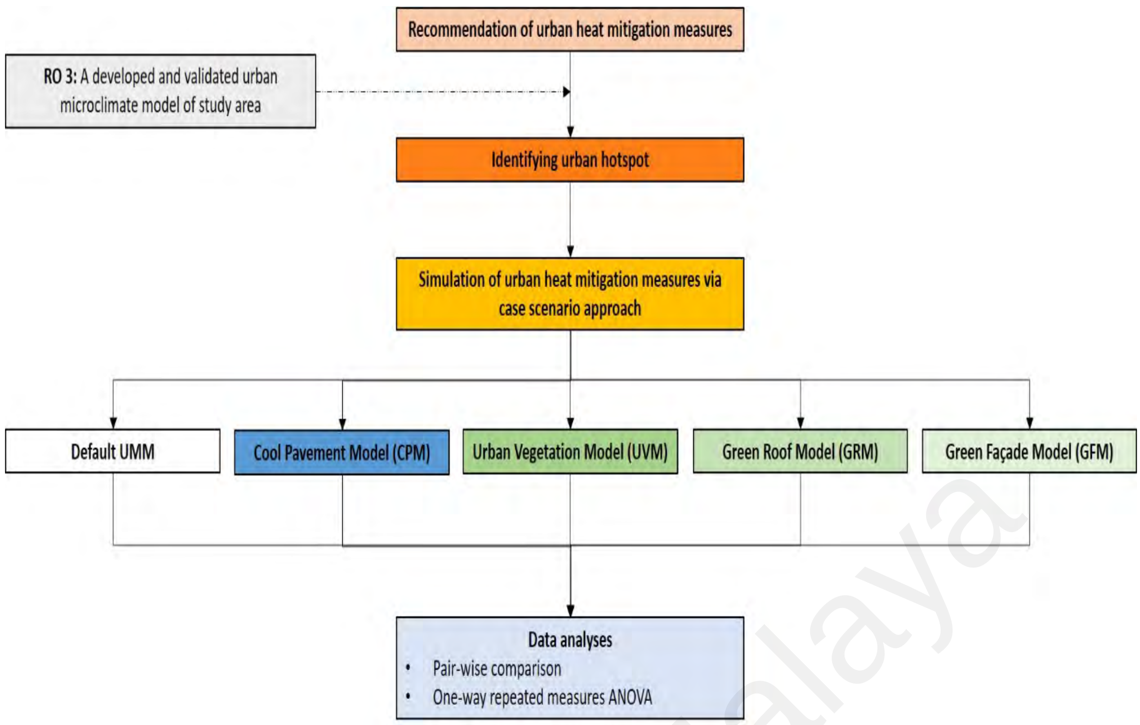


Figure 3.14: Flowchart of recommending urban heat mitigation measures in study area

3.6.1 Identifying urban hotspot in study area

From the UMM developed in Section 3.5, the urban hotspot within the study area is identified. The urban hotspot is defined as a region which is found to have a slower heat dissipation rate as compared to the other simulated area in the UMM. In further analysis, various urban heat mitigation measures were modelled and simulated with ENVI-MET to identify the effectiveness of each mitigation measures in improving the urban microclimate of the identified urban hotspot. The detailed methodology of urban heat mitigation measures is elaborated in the next section.

3.6.2 Exploring urban heat mitigation measures via case study scenario approach

A case scenario approach was carried out to identify effective urban heat mitigation measures towards the improvement of microclimate in the urban hotspot. The urban heat mitigation measures emphasized the approach of urban greening and using cooling materials. The components in the existing urban ecosystem such as pavement, vegetation, building walls and roofs are modified according to the case study scenarios and simulated to predict the subsequent changes to the urban microclimate. The case study scenarios are described in the following section.

3.6.3 Case study scenarios to identify the potential of urban heat mitigation measures

3.6.3.1 Default urban microclimate model (UMM)

The UMM developed from Section 3.5 will served as the baseline for comparison. The model applies standard values of existing urban environment of the study area.

3.6.3.2 Case scenario 1: Cool pavement model (CPM)

In this case scenario, the default UMM is modified to identify the potential of cool pavement materials in urban heat mitigation. The materials that made up the allocated open spaces in the study area is changed from grey concrete to light concrete. The albedo on the light concrete surface is 0.80 while the grey concrete surface is 0.50. The location where the changes are implied corresponds to the other case scenarios to allow a direct comparison between various urban heat mitigation measures. Other parameters of the UMM are left unchanged. The datasheet of the cool pavement material applied in the simulation model is summarized in Table 3.16.

Table 3.16: **Datasheet of cool pavement material in simulation model**

Parameter	Value
Name	Concrete Pavement Light
Database-ID	0100PL
Colour	White
z0 Roughness Length	0.01
Albedo	0.80
Emissivity	0.90

3.6.3.3 Case scenario 2: Urban vegetation model (UVM)

Through this case scenario, the default UMM is modified to identify the potential of urban vegetation in mitigating urban heat. The amount of vegetation in the selected study area is controlled according to the green index proposed by Rui et al. (2018) expressed as follows (Rui et al., 2018):

$$G_g = {(A_{grass} + A_{shrub})}/{A} \qquad \text{(Eq. 10)}$$

Where,

G_g is the percentage of area in which the thermo-physical properties of ground surfaces are changed with vegetation;

A_{grass} and A_{shrub} is the area of grass and shrub in m^2;

A is the total study area in m^2.

According to the green index, 15% of the ground surfaces is replaced with vegetation in the selected study area. Other parameters of the UMM are left unchanged. Besides, a universal form of the plant is used in the model. All the grasses added to the model are 25 cm in height while the trees are 15 m in height with 9 m crown width. The control over defining factors such as plant type is done to evaluate the effect of the described case on the urban microclimate. The datasheet of the grass applied in the simulation model is summarized in Table 3.17.

Table 3.17: Datasheet of grass in simulation model

Parameter	Value
Name	Grass 25 cm
Database-ID	010000
Colour	Light green
Leaf type	Grass
Albedo	0.00
Transmittance	0.30
Plant height	0.25
Root Zone Depth	0.20

The datasheet of the trees applied in the simulation model is summarized in Table 3.18.

Table 3.18: Datasheet of tree in simulation model

Parameter	Value
Name	Tree 15 m, distinct crown layer
Database-ID	000000SK
Colour	Light green
Leaf type	Deciduous
Albedo	0.20
Transmittance	0.30
Plant height	15.00
Root Zone Depth	2.00

3.6.3.4 Case scenario 3: Green façade model (GFM)

In this case scenario, the default UMM is modified to identify the potential of green façade in urban heat mitigation. The buildings found in the study area were applied with green façade. The green façade chosen is the type with air gaps and mixed sandy loam substrate. Other parameters of the existing microclimate model are left unchanged. The datasheet of the green façade applied in the simulation model is summarized in Table 3.19.

Table 3.19: **Datasheet of green façade in simulation model**

Parameter	Value
Name	Green + Sandy Loam Substrate
Database-ID	01AGSS
Colour	Green
Air gap	Yes

3.6.3.5 Case scenario 4: Green roof model (GRM)

In this case scenario, the default UMM is modified to identify the potential of green roof in urban heat mitigation. The buildings found in the study area were applied with a green roof. The green roof chosen is the type with air gaps and mixed sandy loam substrate. Other parameters of the existing microclimate model are left unchanged. The datasheet of the green roof applied in the simulation model is summarized in Table 3.20.

Table 3.20: **Datasheet of green roof in simulation model**

Parameter	Value
Name	Green + Sandy Loam Substrate
Database-ID	01AGSS
Colour	Green
Air gap	Yes

3.6.4 Data analyses

3.6.4.1 Comparison of urban heat mitigation performance

All the case scenarios are simulated in ENVI-MET for 24 hours of a selected day starting from 7.00 am until 6.00 am the day after. A one-way repeated measures ANOVA is conducted for each case scenarios to identify if there are significant changes to the urban microclimate parameters. Data for Ta, WS, RH and Tmrt are extracted from the simulation model. Pairwise comparison is conducted on the simulated microclimate data from each case scenarios (CPM, UVM, GFM and GRM) with the default UMM to identify the potential of each urban heat mitigation measures towards the improvements of urban microclimate in the study area.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

The results obtained in the conduct of the research is presented in this chapter. Due to the transdisciplinary of the objectives, the discussion was merged with the respective results to provide a seamless presentation of findings from the research. The chapter overview is elaborated as follows:

i. Section 4.2 presents the findings from Phase 1 which highlighted the urban microclimate variations near-surface level in the study area.

ii. Section 4.3 presents the findings from Phase 2. Due to the vast findings of human health implications from urban heat exposure, Section 4.3 is allocated to present the findings on the outdoor thermal comfort level in the study area.

iii. Meanwhile, Section 4.4 is allocated to present the findings on heat-related illnesses related to urban heat exposure.

iv. Section 4.5 presents the findings from Phase 3 of the research which highlighted the development and validation of the urban microclimate model for simulation purposes.

v. Lastly, Section 4.6 presents the findings on urban heat mitigation measures which has the best potential in improving urban microclimate in the study area.

4.2 Phase 1: Urban microclimate variations in selected study area

The first RO is to monitor the urban microclimate variations near-surface level in the study area. The findings from Phase 1 of the research is presented in this section.

4.2.1 Continuous monitoring of microclimate variations in selected study area

Continuous monitoring of the urban microclimate on meteorological parameters such as Ta, RH, WS and WD, and SR has been conducted at 2 m height above the surface level from January to December 2018. The data from AWS is extracted and pre-processed to only include meteorological parameters from non-rainy days. The mean and standard deviation of the microclimate variations are presented in Table 4.1.

Table 4.1: The mean and standard deviation of microclimate variations in selected study area

	Ta (°C)	RH (%)	WS (m/s)	SR (W/m^2)
Mean	30.23	69.09	0.63	98.21
Std. Deviation	3.90	13.75	0.57	119.74

The variations in each parameter are further discussed in the following sub-section.

4.2.1.1 The air temperature and relative humidity variations in selected study area

The variations in Ta and RH is presented in Figure 4.1. The monthly average of Ta ranges from 26.97 to 29.27°C while the monthly average of RH ranges from 64.73 to 77.69%. It was observed that the coolest month is in January 2018 while the hottest month was in August 2018. In terms of humidity, August 2018 is found to be the driest as compared to the wettest month in January 2018. These observations could be attributed to the two main monsoon seasons which is the wet northeast monsoon that occurs from November to March and the dry southwest monsoon that occurs from June to September

(Ramakreshnan et al., 2019). Despite the variations in both Ta and RH, the selected study area experienced typical hot-humid tropical climate with mean Ta of 30.23°C (SD=3.90°C) and mean RH of 69.09% (SD=13.75%).

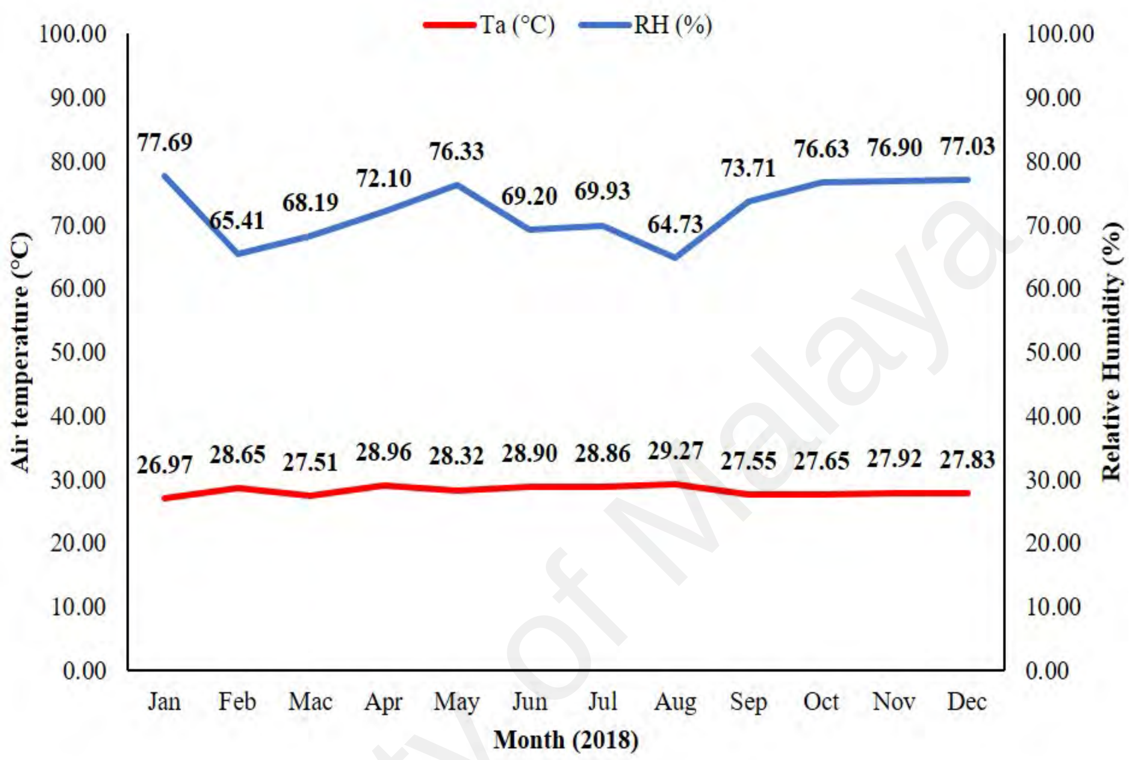


Figure 4.1: **Microclimate variations in air temperature and relative humidity at Masjid Jamek in 2018**

4.2.1.2 The wind speed and direction variation in selected study area

The WS in the selected study area was found to fluctuate from 0.00 to 3.01 m/s while the average WS is recorded at 0.63 m/s (SD=0.57 m/s). In general, the selected study area experiences light air activity throughout the year according to the Beaufort wind force scale, a common empirical measure that relates wind speed to observed conditions on land or at sea as shown in Table 4.2.

Table 4.2: **Beaufort wind force scale**

Beaufort scale	Wind speed (m/s)	Characteristic
0	< 0.5	Calm
1	0.5–1.5	Light air
2	1.6–3.3	Light breeze
3	3.4–5.5	Gentle breeze
4	5.5–7.9	Moderate breeze
5	8–10.7	Fresh breeze

By referring to the WS class of the Beaufort scale, the distribution of WS in the selected study area is presented in Figure 4.2.

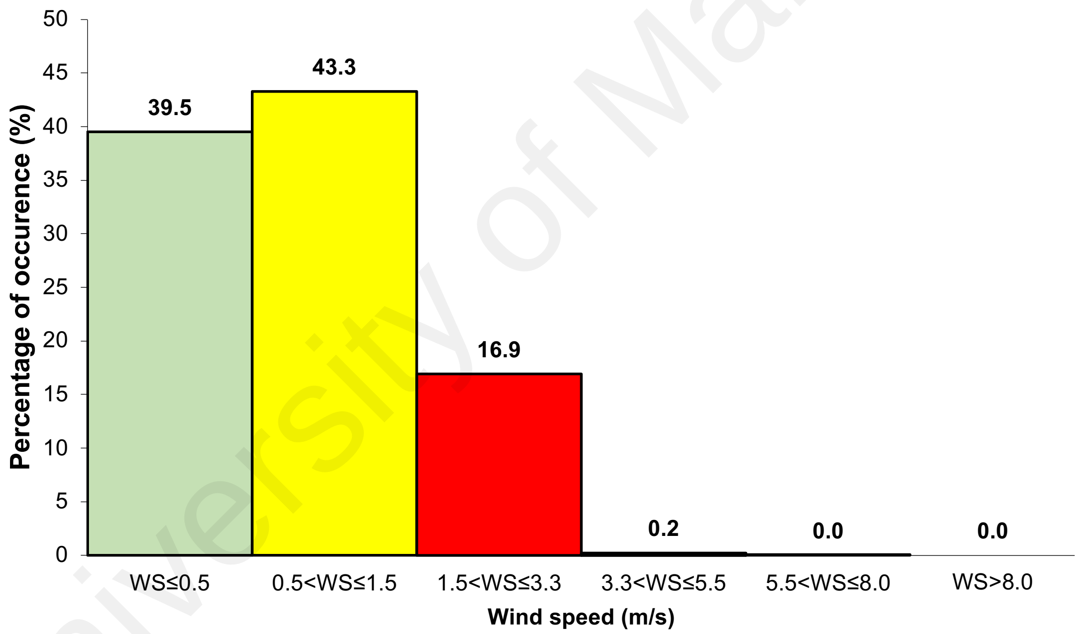


Figure 4.2: **Distribution of wind speed classes at Masjid Jamek in 2018**

Light air activity representing WS of 0.5 to 1.5 m/s is predominant (43.3%) in the study area followed by calm air (39.5%) and a light breeze (16.9%). Influencing factors such as the existence of high-rise buildings, rough pavement surfaces and other obstructing objects could be the reason for explaining the low WS in the study area. The introduction of these elements alters the aspect ratio and surface roughness of the urban morphology which would then contributes to the deterioration of the urban environment. Higher WS is associated with higher effectiveness to remove urban heat and simultaneously contribute to a better OTC level (Ng, 2009; Ng et al., 2011; Hanipah et al., 2016). From an OTC study conducted in Hong Kong, a wind speed of 1.6 m/s is required for urban communities to achieve thermal comfort (Cheng et al., 2012; Yuan & Ng, 2012). Unfortunately, there is only a 0.2% occurrence of gentle breeze representing WS of 3.4 to 5.5 m/s.

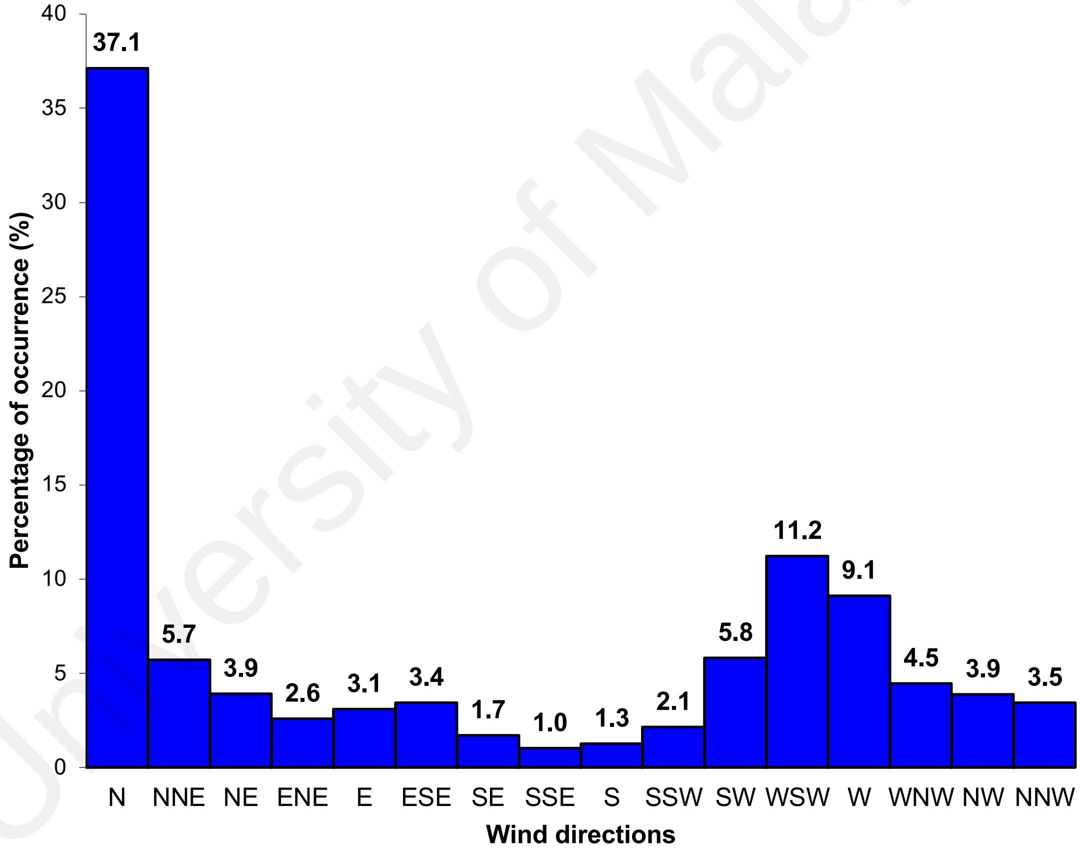


Figure 4.3: **Distribution of wind directions at Masjid Jamek in 2018**

In terms of WD, the microclimate observations are divided into sixteen wind direction groups as shown in Figure 4.3. The wind is blowing predominantly from the North direction (37.1%). Other wind directions that account for the remaining 62.9% indicates that there is a resultant vector to the wind pattern in the study area. A wind-rose diagram is plotted using the wind speed and direction to summarize the wind variability in the study area. The wind-rose diagram is presented in Figure 4.4.

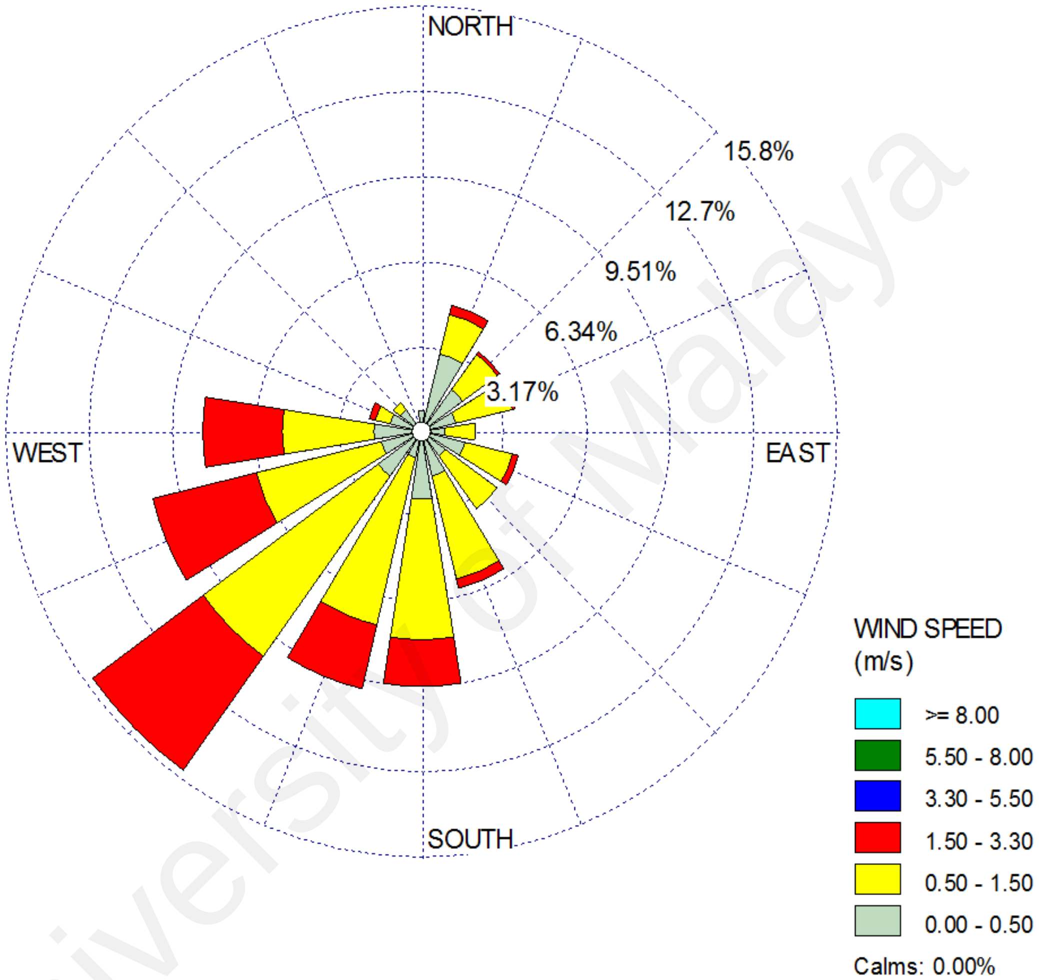


Figure 4.4: **Wind-rose diagram representing wind variability in MJ**

The magnitude of the resultant vector accounting for 36% of the wind variability is most dominant from 209° or the southwest direction in the study area.

4.2.1.3 The solar radiation variation in selected study area

The SR variations in the study area are shown in Figure 4.5. The monthly average SR ranges from 241.24 to 364.18 W/m^2. Daily, the study area receives an average of 98.21 W/m^2 (SD=119.74 W/m^2) of SR. The high variation in SR is mainly attributed to the unpredicted cloud cover in the tropical region.

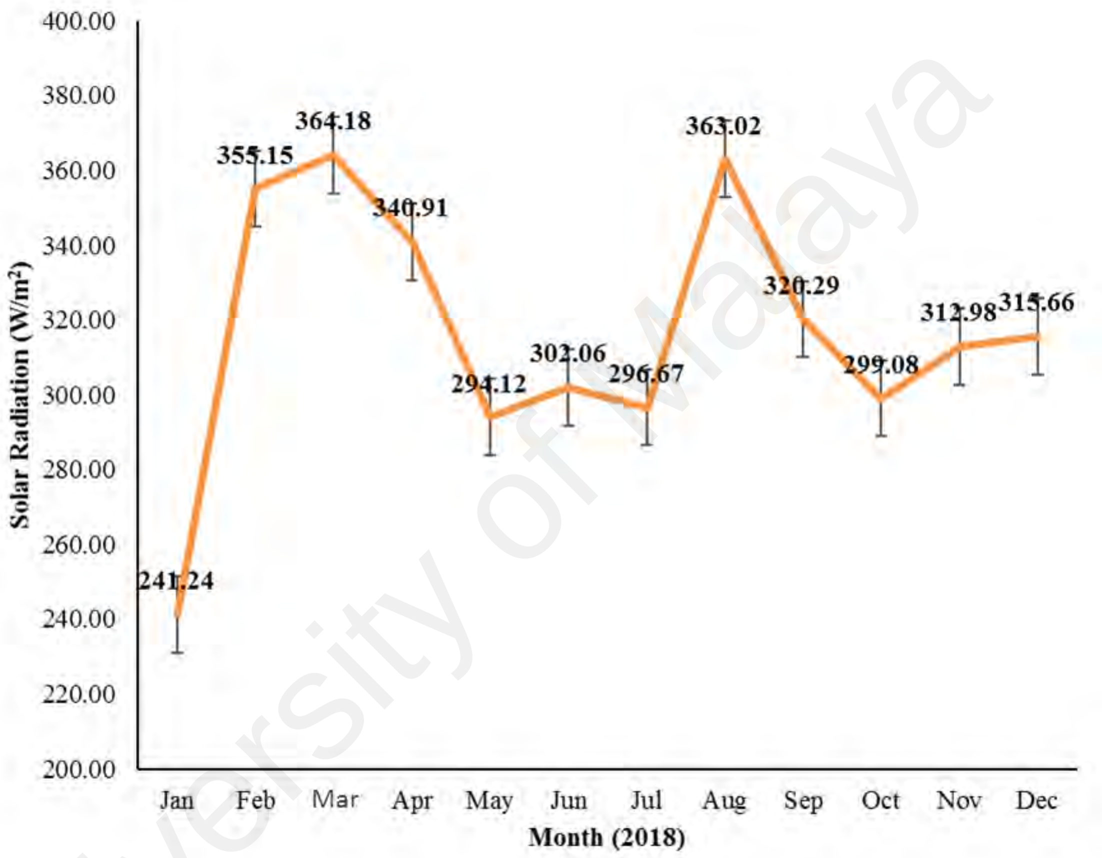


Figure 4.5: **Microclimate variations in solar radiation at Masjid Jamek in 2018**

4.2.1.4 The diurnal variations of microclimate parameters in selected study area

Each meteorological data collected on a 5 minutes-interval were grouped to the nearest past hour to identify the diurnal variations in microclimate parameters. For example, data collected on 12:05, 12:30 and 12:55 were all rounded to 12:00. The daily hour-average of each microclimate parameters is summarized in Table 4.3.

Table 4.3: Daily hour-average of microclimate parameters

Hours	Ta (°C)	RH (%)	WS (m/s)	*SR (W/m^2)
1	29.86	68.52	0.61	ND
2	31.11	65.59	0.77	ND
3	32.02	63.81	0.90	ND
4	32.87	61.33	0.97	ND
5	33.20	59.56	1.02	ND
6	33.14	59.14	1.10	ND
7	32.66	60.26	1.13	ND
8	32.19	61.36	1.09	26.35
9	31.57	62.77	0.93	152.38
10	31.11	63.60	0.83	325.74
11	31.01	64.02	0.71	478.83
12	31.04	63.90	0.76	584.53
13	31.13	63.58	0.76	624.57
14	31.45	62.90	0.79	619.01
15	31.42	63.04	0.77	566.57
16	31.34	63.24	0.74	482.83
17	30.92	64.51	0.74	336.83
18	30.24	66.07	0.74	186.43
19	29.55	67.87	0.65	61.84
20	28.94	69.51	0.60	ND
21	28.65	70.27	0.41	ND
22	28.56	70.67	0.41	ND
23	28.73	70.42	0.41	ND
24	29.03	70.27	0.51	ND

***ND is the abbreviation for Not Detected**

In terms of daily variations, the Ta and RH were observed to show an inverse relationship. The daily mean of Ta is found to be 30.91°C (SD=1.42°C) while the daily mean of RH is 64.84% (SD=3.59%). The trend of daily diurnal variations for Ta and RH is as shown in Figure 4.6.

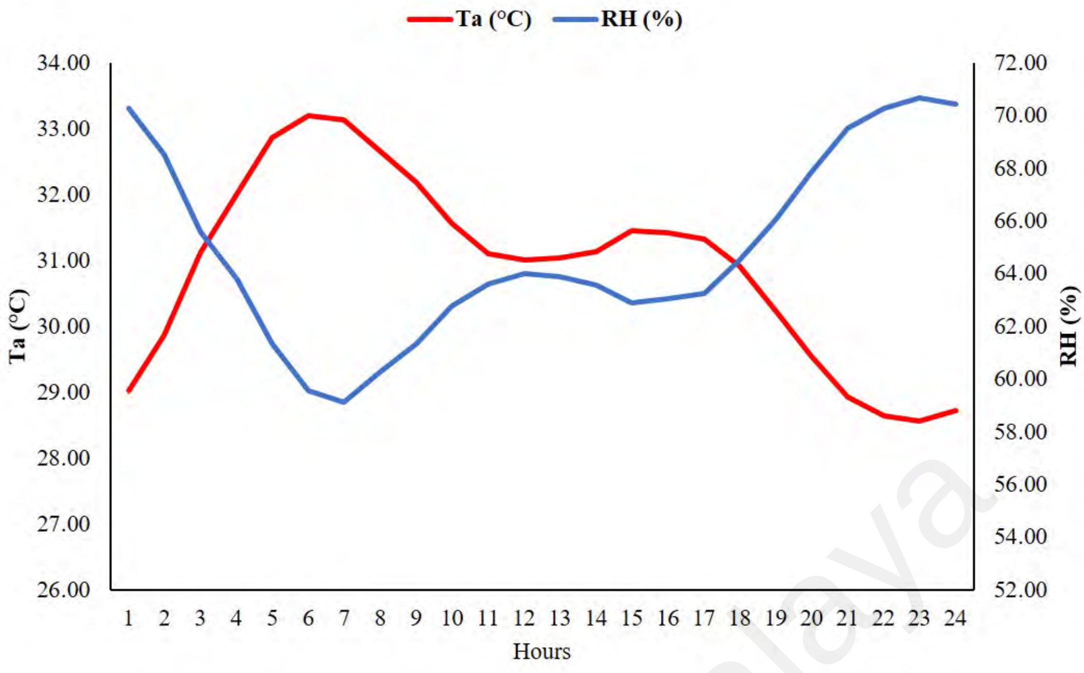


Figure 4.6: **Daily diurnal variation of air temperature and relative humidity**

In terms of wind activity, the daily mean WS was found to be 0.76 m/s (SD=0.21 m/s). The trend of daily diurnal variations for WS is as shown in Figure 4.7.

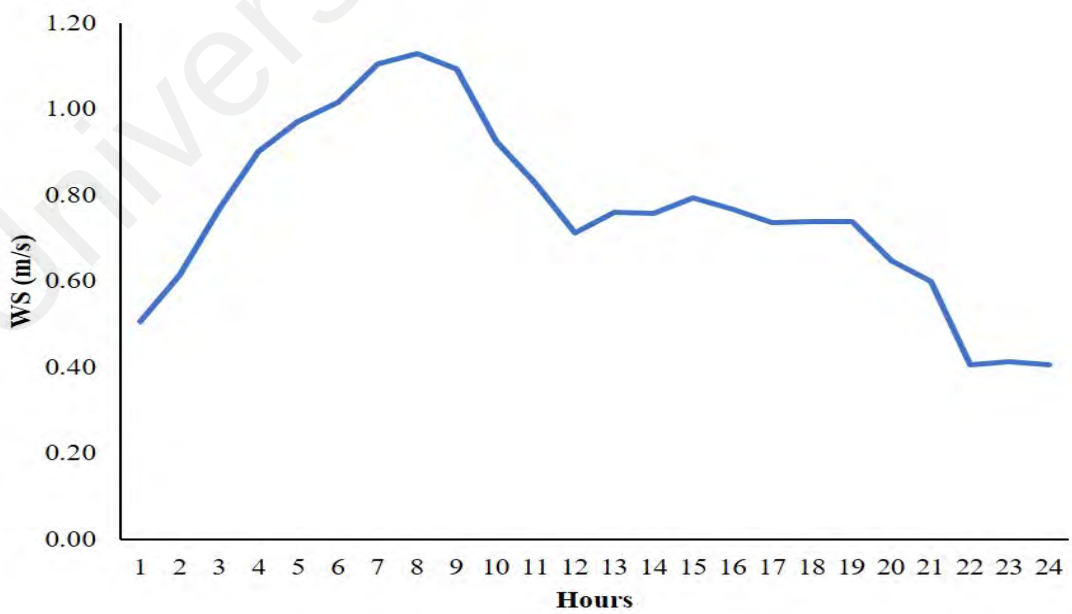


Figure 4.7: **Daily diurnal variation of wind speed**

In a diurnal manner, it was observed that the WS showed a gradual increase from 0.51 m/s at 1:00 am to 1.13 m/s at 7:00 am before it starts decreasing after sunrise. The WS is quite stagnant from 0.74 to 0.79 m/s during 12:00 pm to 7:00 pm before further decreasing to 0.41 m/s at 10:00 pm. The low WS especially few hours after sunset is something that needs to be addressed as it plays a significant role in ameliorating the trapped urban heat in the city centre.

The daily variation of SR is quite straightforward as shown in Figure 4.8. The AWS started to record some SR beginning 8:00 am where the sun starts to rise and peaked at 624.57 W/m^2 around 1:00 pm. The SR started to show drastic reduction after 3:00 pm and as it approaches sunset around 7:00 pm, the SR is near to 0 W/m^2. No SR was recorded after 7:00 pm. Daily, the study area is expected to receive an average of 370.49 W/m^2 with a standard deviation of 220.17 W/m^2.

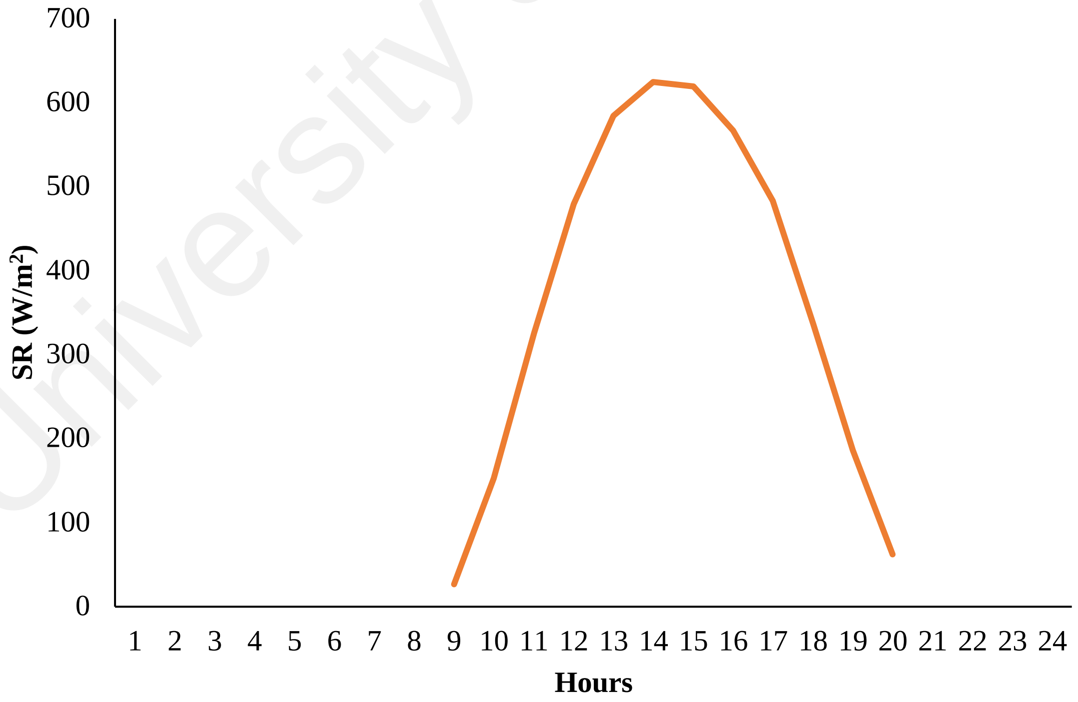


Figure 4.8: Daily diurnal variation of solar radiation

In summary, the diurnal variations (on a non-rainy day) of microclimate parameters especially for Ta and RH were found to show a similar trend as compared to the monthly variations from continuous monitoring. However, the diurnal variations in WS and SR were found to fluctuate more daily as compared to their monthly average. The high SR variability could be influenced by the cloud variability in the troposphere level while the variation in WS could be associated with the complex land-surface interaction. Besides that, the two monsoonal seasons which is the Northeast (November–March) and Southwest (June–September) monsoon may have impelling effects on the WS variations as well. Although the diurnal variations in WS and SR could be observed, the evidence of the causal factor was unexplored in this study. Nonetheless, the selected study area was found to exhibit a typical characteristic of a tropical climate despite the variation across the temporal scale. The relationship between the microclimate parameters is discussed in the next sub-section.

4.2.1.5 The relationship between the microclimate parameters

A Pearson product-moment correlation coefficient analysis is conducted to identify the strength of relationship among the four selected meteorological variables. Preliminary analyses were performed to ensure no violation of the assumptions of normality, linearity and homoscedasticity. The correlation between the four meteorological parameters is summarized in Table 4.4.

Table 4.4: Pearson correlation of microclimate parameters

	Ta	RH	WS	SR
Ta	-			
RH	-0.935**	-		
WS	0.584**	-0.614**	-	
SR	0.763**	-0.664**	0.640**	-

** Correlation is significant at the 0.01 level (2-tailed).

In general, all variables are significantly correlated at the 0.01 level (2-tailed). There is a strong and negative correlation for Ta with RH (r^2=-0.935, n=864, p<0.0.1). This could be explained via the evaporation process on urban surfaces which increases the RH due to an increase in water vapour pressure and a decrease in saturation water vapour pressure (Kim & Baik, 2002; Liu et al., 2007). As a result, the surface air temperature decreases due to the evaporative cooling effects. This explains the strong and inverse relationship between Ta with the RH. Meanwhile, the association among other pairs of meteorological parameters are in agreement with the findings from Ramakreshnan et al. (2019).

4.2.2 A comparison of microclimate data from Automated Weather Station and MetMalaysia

A comparison of meteorological data from both AWS and MetMalaysia is conducted to identify if the existing meteorological data from the MetMalaysia's principal monitoring station would be adequate for this current microclimate study. A total of 864 data sets were included for analysis. A Pearson product-moment correlation coefficient analysis is conducted to elucidate the strength of relationship among the four selected meteorological variables from AWS and MetMalaysia. Preliminary analyses were performed to ensure no violation of the assumptions of normality, linearity and homoscedasticity. The descriptive statistics and correlation findings are summarized in Table 4.5.

Table 4.5: Descriptive statistics and correlation findings of meteorological data from AWS and MetMalaysia (n=864)

Meteorological parameters	AWS		MetMalaysia		Correlation, r
	Mean	**SD**	**Mean**	**SD**	
Ta	30.23	3.90	29.44	2.50	-0.098^{**}
RH	69.09	13.75	68.07	12.36	0.119^{**}
WS	0.63	0.57	1.50	0.85	0.121^{**}
SR	98.21	119.74	357.48	265.11	0.194^{**}

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

The data for Ta, RH, WS and SR were compared because they impose significant influence on the urban thermal environment. As observed through descriptive analysis, the mean and standard deviation difference for Ta and RH from both stations are relatively small. In contrast, the mean and standard deviation difference for the WS and SR from both stations are relatively large. In terms of linear association, there is a weak and negative correlation for Ta (r= -0.098, n=864, p<0.0.1), while there is a positive and weak correlation for RH (r=0.119, n=864, p<0.0.1), WS (r=0.121, n=864, p<0.0.1) and SR (r=0.194, n=864, p<0.0.1).

In short, all four selected meteorological variables from MetMalaysia were weakly correlated with the data sets from AWS. One of the possible explanations is the influence of built-environment around the monitoring stations. Physical site characteristics such as horizontal surface cover (the type of land-use, pavement type, etc.) and vertical structure (buildings, artificial structures, trees, etc.) have strong influence towards the variations in microclimate conditions from one urban outdoor space to another. For example, buildings tend to provide shading to the surrounding vicinity thus reducing direct solar radiation. Besides that, buildings and paved surfaces can also alter wind movements due to the difference in surface roughness. Hence, the AWS placed in the selected study area will be able to evaluate urban heat exposure at human height level more accurately compared to MetMalaysia's principal monitoring station.

4.2.3 Summary

In summary, continuous monitoring of the meteorological variables such as Ta, RH, WS and wind direction, and SR is conducted at 2 m height using a customized automated weather station (AWS). Despite the variations in both Ta and RH, the selected study area experienced typical hot-humid tropical climate with mean Ta of 30.23°C (SD=3.90°C) and mean RH of 69.09% (SD=13.75%). Light air activity representing WS of 0.5 to 1.5 m/s is predominant (43.3%) in the study area with the average WS recorded at 0.63 m/s (SD=0.57 m/s). Influencing factors such as the existence of high-rise buildings, rough pavement surfaces and other obstructing objects could be the reason for explaining the low WS in the study area. In terms of SR, the study area receives an average of 98.21 W/m^2 (SD=119.74 W/m^2) of SR daily. The high variation in SR is mainly attributed to the unpredicted cloud cover in the study area.

The diurnal variations (on a non-rainy day) of microclimate parameters especially for Ta and RH were found to show a similar trend as compared to the monthly variations from continuous monitoring. However, the diurnal variations in WS and SR were found to fluctuate more daily as compared to their monthly average. The high SR variability could be influenced by the cloud variability in the troposphere level while the variation in WS could be associated with the complex land-surface interaction. Besides that, the two monsoonal seasons which is the Northeast (November–March) and Southwest (June–September) monsoon may have impelling effects too on the WS variations. Although the diurnal variations in WS and SR could be observed, the evidence of the causal factor was unexplored in this study. Nonetheless, the selected study area was found to exhibit a typical characteristic of a tropical climate despite the variation across the temporal scale.

The results obtained from the AWS is compared with the data from MetMalaysia to identify the acceptability of existing meteorological data for microclimate studies. In a nutshell, all four selected meteorological variables from MetMalaysia were weakly correlated with the data sets from AWS. Hence, the AWS placed in the selected study area can evaluate urban heat exposure more accurately as compared to MetMalaysia's principal monitoring station.

4.3 Phase 2: A comprehensive evaluation of impact from urban heat towards outdoor thermal comfort level in selected study area

The second RO is to evaluate and associate urban heat with OTC and HRIs in the study area. The findings from Phase 2 of the research is presented in this section. Due to the vast findings in Phase 2, the findings related to OTC is presented in Section 4.3 while the findings related to HRIs are presented in Section 4.4. The microclimate data from section 4.2 is used to evaluate the physiological OTC indices while a large-scale questionnaire survey was conducted to evaluate the psychological OTC thermal responses. The OTC level of the urban communities is elaborated in the following sub-sections.

4.3.1 Sociodemographic of respondents in the selected study area

The data collected using a structured questionnaire was conducted from July 2018 to December 2018. While most of the survey was conducted on weekdays, the survey was also conducted during the weekends to maximize response rate. In total, 1160 eligible responses were collected and included for subsequent data analysis. It was found that slightly more than half of the participants are females (n= 634, 54.7%), while males make up the other 45.1% (n=523) of the total respondents in this study. In terms of age distribution, the age gap is 65 years with the youngest respondent being 15 years old while the oldest is 80 years old. The mean age is 27 years (SD=10.6 years). According to the World Health Organization age group classification, the respondents are the majority of adults (n=948, 81.7%) within the age of 19 to 64 years old. In terms of ethnicity, majority are Malays (n=511, 44.1%) followed by Chinese (n=436, 37.6%), Indians (n=81, 7.0%) and other ethnicities (n=129, 11.1%). The respondents of this study are well educated with 58.6% (n=680) having tertiary level education and the remaining 41.1% (n=477) having at least secondary level education and below. While a majority (n=737, 63.5%)

are staying in KL, there are also a group of people (n=423, 36.5%) that are not staying in KL. In average, the respondents are spending about 6 hours (SD=4.0 hours) at outdoors in a day for various activities such as commuting (n=681, 58.7%), working (n=145, 12.5%) and doing sports and leisure (n=343, 29.6%). The sociodemographic of the respondents are presented in Table 4.6.

Table 4.6: Sociodemographic of respondents

		Frequency (%) (n=1160)
Gender		
	Male	523 (45.1)
	Female	634 (54.7)
	Unwilling to disclose	3 (0.2)
Age		
	Young adults (< 18 years old)	191 (16.5)
	Adults (19 – 64 years old)	948 (81.7)
	Elderlies (> 65 years old)	7 (0.6)
	Unwilling to disclose	14 (1.2)
Ethnicity		
	Malay	511 (44.1)
	Chinese	436 (37.6)
	Indian	81 (6.9)
	Others	132 (11.4)
Education level		
	Secondary level and below	480 (41.4)
	Tertiary level	680 (58.6)
Occupation		
	Student	598 (51.6)
	Self-employed	99 (8.5)
	Government workers	98 (8.4)
	Private sector workers	286 (24.7)
	Unemployed	54 (4.7)
	Others	25 (2.1)
Monthly income		
	< RM 1000	77 (6.6)
	RM 1001 - 2000	127 (10.9)
	RM 2001 - 3000	79 (6.8)
	RM 3001 - 4000	46 (4.0)
	> RM 4001	83 (7.2)
	Unwilling to disclose	748 (64.5)
Residential status		
	In Kuala Lumpur	737 (63.5)
	Not in Kuala Lumpur	423 (36.5)
Duration spent outdoors (hours in a day)		
	< 3 hours	239 (20.6)
	3 - 5 hours	258 (22.2)
	5 - 9 hours	355 (30.6)
	> 9 hours	255 (22.0)
	Uncertain	53 (4.6)
Main outdoor activities		
	Commuting	681 (58.7)
	Working	145 (12.5)
	Sports and Leisure	343 (29.6)

In terms of transport mode, 57% of the respondents depended on public transport facilities and non-motorized vehicles while other respondents which accounts for 43% used private motorized vehicles as shown in Figure 4.9.

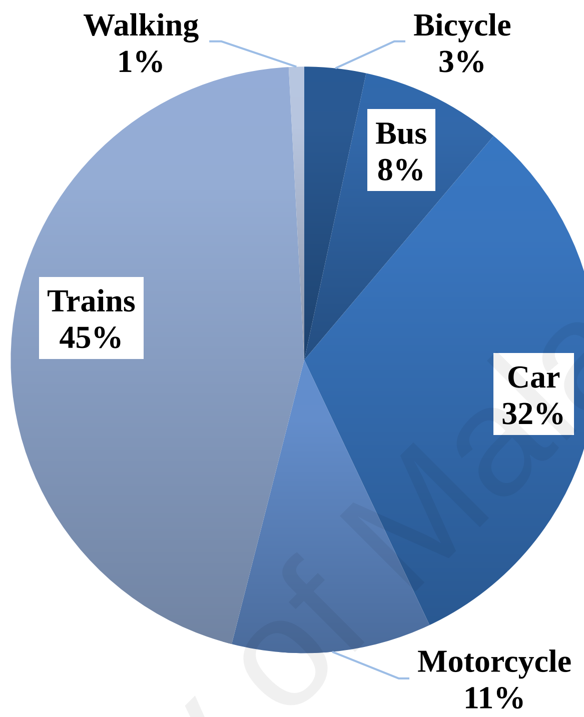
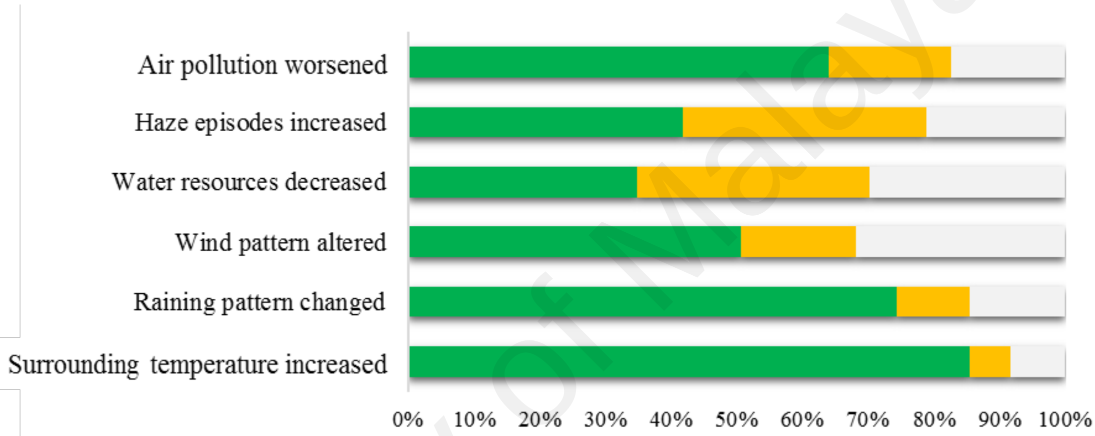


Figure 4.9: Main transport mode of the respondents

Despite the study area being in the walking distance from three train stations, i.e., Plaza Rakyat, Masjid Jamek and Pasar Seni station, and one bus hub located in Kota Raya, more than half of the respondents depended on a private motorized vehicle as their main mode of transport. Improving the efficiency of the transport system in KL and the OTC level in the urban environment could be one of the promising ways to promote urban walkability.

4.3.1.1 Knowledge and awareness level on surrounding environment

In the structured questionnaire, a section was allocated to assess the level of awareness towards the changes in the surrounding environment among 1160 respondents from the urban communities. A total of six questions are asked with regards to air pollution level, haze episodes, water resources, wind pattern, raining pattern and the surrounding temperature. A stacked bar chart is used to present the level of awareness of the urban communities towards the surrounding environment as shown in Figure 4.10.



	Surrounding temperature increased	Raining pattern changed	Wind pattern altered	Water resources decreased	Haze episodes increased	Air pollution worsened
Yes	992	864	587	405	485	742
No	73	129	204	410	430	217
Don't know	95	167	369	345	245	201

Figure 4.10: Urban communities' level of awareness towards the surrounding environment

The urban community is found to be aware of the surrounding environment particularly when it comes to the surrounding temperature increase (n=992, 85.5%), raining pattern changes (n=864, 74.5%) and air pollution level worsen (n=742, 64.0%). The moderate awareness towards wind pattern changes (n=587, 50.6%) may be because wind pattern alteration is less prominent as compared to the other aforementioned environmental changes. Meanwhile, the occurrence of haze and water resources disruption which does not happen regularly could be the explanation for the lower level of respondents reporting having experienced these environmental changes recently.

4.3.2 The assessment of physiological outdoor thermal comfort level

The microclimate data from AWS is used to calculate the physiological OTC indices to express the physiological heat strain of respondents in the study area. As the microclimate monitoring is done at a precision of 5-minute interval, the OTC indices were also determined with the same precision. Although there are 1160 eligible respondents, only 864 sets of microclimate data were included for the assessment of physiological OTC indices. This is because there are situations where more than one respondents answer the questionnaire within the same 5-minute timeframe. Hence, the duplication of microclimate data was excluded while assessing physiological OTC indices. Table 4.7 summarizes the descriptive statistics of the selected OTC indices in this study.

Table 4.7: Descriptive statistics of selected outdoor thermal comfort indices

OTC indices	**n**		**Mean**	**Std. Deviation**	**Min.**	**Max.**
	Valid	Missing				
PET	864	-	29.45	2.106	24.00	39.00
PMV	864	-	1.59	0.669		
SET	864	-	26.69	2.615	18.00	35.00
UTCI	501	363	32.41	2.215	26.00	42.00
WBGT	864	-	26.46	1.292	24.20	31.44

Among the five selected OTC indices, only UTCI was found to have issues with missing data. This is because the minimum WS required at 10 m is at least 0.5 m/s in evaluating UTCI. While the daily mean WS exceeds the threshold value, there are moments with WS lesser than 0.5 m/s. As aforementioned, when there are instantaneous moments with no wind activity, the UTCI could not be evaluated and a value of 9999 will be presented instead. For data analysis purposes, the value 9999 were all transformed to missing values as they possess the characteristics of outliers in statistical analysis. On a side note, although the 5 minutes' interval precision could explain more accurately the daily diurnal variations of the microclimate, certain situations may need longer time-weighted average values instead. For example, when UTCI is chosen as the OTC index to express physiological strain, hourly or daily average might be more representative as compared to average in minutes. The interpretation of physiological heat strain for table 4.7 is summarized in Table 4.8.

Table 4.8: Interpretation of physiological heat strain expressed through selected outdoor thermal comfort indices

OTC indices	Mean	Std. Deviation	Interpretation according to respective OTC classes
PET	29.45	2.106	Slight heat stress
PMV	1.59	0.669	Slightly warm to Warm
SET	26.69	2.615	Slightly warm and unacceptable
UTCI	32.41	2.215	Strong heat stress
WBGT	26.46	1.292	Strong heat stress

In general, it was found that all five OTC indices are expressing similar physiological heat strain despite having different principals in evaluating thermal heat stress. The evaluation which is mainly based on environmental and individual factors may vary depending on the assumptions towards the thermal environment. For example, SET assumes that the Tmrt equals the Ta in a thermal environment may or may not be entirely true in the existing outdoor environment. According to the interpretation of heat stress, as shown in Table 4.8, it was observed that PET, PMV and SET are reporting less severe conditions as compared to UTCI and WBGT. Albeit the difference in heat stress class, the sensitivity analysis on the interpretation would not yield meaningful findings here. This is because the ultimate goal is not to find the best OTC indices among the chosen five but rather identifying the one OTC indices that may serve as a proxy to explain the reported psychological thermal sensation administered through the questionnaire survey. In further analysis, the correlation between the five selected OTC indices is conducted and presented in the next sub-section.

4.3.2.1 Correlation of selected outdoor thermal comfort indices

A Pearson product-moment correlation coefficient analysis is conducted to identify the strength of relationship among the five selected OTC indices. Preliminary analyses were performed to ensure no violation of the assumptions of normality, linearity and homoscedasticity. The correlation among the five selected OTC indices is summarized in Table 4.9.

Table 4.9: Pearson correlation of selected outdoor thermal comfort indices

	PET	PMV	SET	UTCI	WBGT
PET	-				
PMV	0.913**	-			
SET	0.882**	0.648**	-		
UTCI	0.956**	0.957**	0.931**	-	
WBGT	0.684**	0.855**	0.447**	0.967**	-

** Correlation is significant at the 0.01 level (2-tailed).

It was found that all OTC indices are statistically correlated at $p<0.01$. UTCI correlated very well with other OTC indices, i.e., with PET ($r=0.956$, $n=501$, $p<0.01$), PMV ($r=0.957$, $n=501$, $p<0.01$), SET ($r=0.931$, $n=501$, $p<0.01$) and WBGT ($r=0.967$, $n=501$, p<0.01) which is in line with the findings from Blazejczyk et al. (2012). The weakest correlation was found to be between WBGT with SET (r=0.447, n=864, p<0.01), while other OTC indices show a strong positive correlation which ranges from r=0.648 to r=0.967. The weak correlation could be related to the assumptions that the Tmrt equals the Ta while evaluating SET. In a dynamic outdoor environment, the Tmrt may not always be equal to the Ta because any instantaneous change in cloud cover would immediately affect the readings of Tmrt as compared to the Ta. With that being said, the usage of SET in a tropical climate may not entirely be recommended as the cloud activity greatly varies in these regions.

As existing thermal comfort indices vary widely, it is difficult to decide on which is the most representative index. Similarly, it is also difficult to recommend one specific index for OTC studies in the tropical climate or other regions in the world. From the literature review, PET is identified as the most commonly used OTC index in the tropical region of SEA (Fong et al., 2019). Therefore, PET is chosen to be correlated with the psychological OTC in further analysis.

4.3.2.2 Prevalence of physiological heat strain expressed through PET

The prevalence of physiological heat strain expressed through PET index is presented in this sub-section. The 7-point thermal sensation scale of PET is dichotomized into two groups representing positive thermal sensation (slightly warm, hot and very hot) and, neutral and negative thermal sensation (neutral, slightly cool, cold and very cold). The mean and standard deviation of the thermal sensation expressed via PET is summarized in Table 4.10.

Table 4.10: Mean and standard deviation of thermal sensations expressed via Physiological Equivalent Temperature

Variables	Participants (n = 864)	PET Index (°C)	95% CI	
	n (%)	Mean ± SD	Lower	Upper
Thermal sensations				
Positive Thermal Sensation	321 (37.2)	31.48 ± 1.96	31.27	31.70
Neutral and Negative Thermal Sensation	543 (62.8)	28.22 ± 0.94	28.14	28.30

It was found that a majority (n=543, 62.8%) reported neutral and negative thermal sensation while only 37.2% (n=321) reported positive thermal sensation. The mean for positive thermal sensation was found to be 31.48°C PET (SD=1.96°C PET) while the mean for neutral and negative thermal sensation was found to be 28.22°C PET (SD=0.94°C PET). Further univariate analysis was conducted to identify the association of thermal sensations reported in PET with selected sociodemographic variables as summarized in Table 4.11.

Table 4.11: Prevalence of thermal response expressed in Physiological Equivalent Temperature according to sociodemographic

Variable	Participants	Physiological Equivalent Temperature		OR (95% CI)	p-value
		Positive Thermal Response	Neutral and Negative Thermal Response		
	n (%)	n (%)	n (%)		
Gender (n = 864)					**0.670**
Male	401 (46.4)	152 (17.6)	249 (28.8)	1.06 (0.81, 1.40)	
Female	463 (53.6)	169 (19.6)	294 (34.0)	Reference	
Age group (n = 858)					**0.113**
< 20 years	311 (36.2)	120 (14.0)	191 (22.3)	1.45 (1.01, 2.09)	
20 -23 years	138 (16.1)	53 (6.2)	85 (9.9)	1.44 (0.92, 2.25)	
24 - 31 years	184 (21.4)	75 (8.7)	109 (12.7)	1.59 (1.06, 2.39)	
> 31 years	225 (26.2)	68 (7.9)	157 (18.3)	Reference	
Ethnicity (n = 846)					**0.002***
Malay	406 (48.0)	176 (20.8)	230 (27.2)	1.89 (1.00, 3.55)	
Chinese	323 (38.2)	98 (11.6)	225 (26.6)	1.07 (0.56, 2.05)	
Indian	65 (7.7)	25 (3.0)	40 (4.7)	1.54 (0.71, 3.37)	
Others	52 (6.1)	15 (1.8)	37 (4.4)	Reference	
Duration spent outdoors in a day (n = 840)					**0.814**
< 3 hours	197 (23.5)	75 (8.9)	122 (14.5)	0.92 (0.61, 1.39)	
3 - 5 hours	275 (32.7)	98 (11.7)	177 (21.1)	0.83 (0.56, 1.22)	
5 - 9 hours	191 (22.7)	72 (8.6)	119 (14.2)	0.90 (0.59, 1.37)	
> 9 hours	177 (21.1)	71 (8.5)	106 (12.6)	Reference	

In general, those that reported positive thermal response are found to be female (n=169, 19.6%), less than 20 years old (n=120, 14.0%), Malay (n=176, 20.8%) and spent 3 to 5 hours in a day at outdoors (n=98, 11.7%). In terms of association, only ethnicity (p=0.002) was found to be significantly associated with expressing thermal response while gender (p=0.670), age group (p=0.113) and duration spent outdoors in a day (p=0.814) were not significantly associated. The Malays are 1.9 times (OR=1.89, 95% CI: 1.00, 3.55) more likely to report positive thermal response as compared to other ethnicities. In comparison, Chinese were found to be 1.1 times (OR=1.07, 95% CI: 0.56, 2.05) more likely while Indian was found to be 1.5 times (OR=1.54, 95% CI: 0.71, 3.37) more likely to report positive thermal response as compared to other ethnicities. In initial deduction, the reason why the Malays are almost twice as likely to report positive thermal sensation could be associated with the duration of exposure. However, in later findings, the insignificant association between thermal response and duration spent outdoors in a day rebuts the aforementioned deduction.

The fact that there is no significant association of duration of exposure with thermal sensation hints two possibilities. First of all, the diurnal changes in the microclimate were deemed to have a negligible influence on the urban community despite the long hours of exposure. Secondly, the urban community have developed a mentality to falsely accept the environment through adjusting their perception of the thermal environment which is known as a type of adaptive behaviour. With that being said, this highlighted one of the limitations in physiological OTC to explore underlying factors affecting an individual to express their true OTC level. The influence of duration of exposure on OTC is further discussed in Section 4.3.5. In the following sub-sections, the psychological OTC as expressed through the subjective questionnaire is analysed in the hope to shed some light to unravel the true OTC level of the urban communities in the selected study area.

4.3.3 The assessment of psychological outdoor thermal comfort level

The psychological OTC is an indication of the perceived mind towards the thermal environment as compared to the physiological OTC which is an indication of what the human body feels. In general, the psychological OTC consists of the sensation, acceptance, preference and the comfort level towards the heat in a given thermal environment. The findings from the large-scale questionnaire are elaborated in the following sub-sections.

4.3.3.1 The thermal sensation of the urban community

The thermal sensation is an indication of how the respondent feels towards the thermal environment while being exposed to urban outdoor spaces. The summary of thermal sensation votes (TSV) is presented in Table 4.12.

Table 4.12: Summary of thermal sensation vote

		Value	n	Percent
n	Valid	1144		
	Missing	16		
Central Tendency and Dispersion	Mean	1.30		
	Std. Deviation	1.350		
Labelled Values	-3	Very cold	1	0.1%
	-2	Cold	38	3.3%
	-1	Slightly cool	117	10.1%
	0	Neutral	132	11.4%
	1	Slightly warm	234	20.2%
	2	Hot	421	36.3%
	3	Very hot	201	17.3%

The mean of TSV was found to be 1.3, indicating that on average, the respondents in the study area is either slightly warm or hot. In terms of distribution, 73.8% (n=856) of the respondents reported positive thermal sensation, while 24.8% (n=288) reported neutral and negative thermal sensation. The distribution of TSV is shown in Figure 4.11.

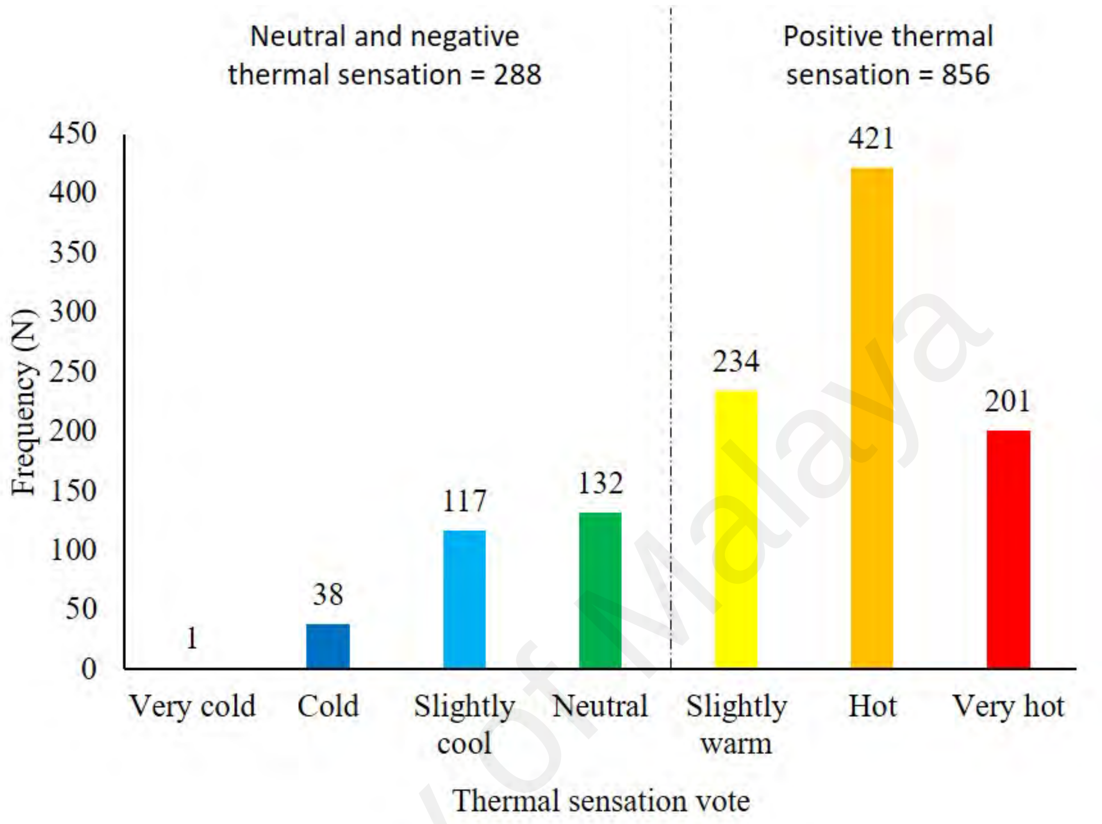


Figure 4.11: Distribution of thermal sensation vote

In general, the graph of TSV was found to be negatively skewed, where more responses were found signifying warm to hot sensation. It is known that the interpretation of scales to express thermal sensations can be bias because of climate, season and language (Schweiker et al., 2020). In the current study, the response for slightly warm (n=234, 20.2%), hot (n=421, 36.3%) and very hot (n=201, 17.3%) were quite distinguished from one another. This could be associated with the modified ASHRAE scale which enables respondents to better express their thermal sensation in a tropical climate. Interestingly, those who reported slightly cool (n=117, 10.1%) and neutral (n=132, 11.4%) sensation were found to be almost equal. This implies that the respondents might presume both expressions of slightly cool and neutral to be similar. The expression of the terms could be reviewed in future studies to ensure a better reporting of the actual thermal sensation.

Interestingly, the findings from psychological OTC as shown in Figure 4.11 which revealed a majority (n=856, 73.8%) expressing positive thermal response contradicts with the findings from physiological OTC (n=321, 37.2%) as shown in Table 4.11. In many OTC studies, there is a tendency for the physiological OTC assessment approach to under-report the actual OTC level in any given thermal environment (Nikolopoulou, 2011). Through this comparison, it proves that only accounting on physiological OTC is insufficient in any OTC related studies.

4.3.3.2 The thermal acceptance of urban community

The thermal acceptance is an indicator for respondents to express their acceptability towards the thermal environment in the urban outdoor spaces. The findings on thermal acceptance vote are summarized in Table 4.13.

Table 4.13: Summary of thermal acceptance vote

		Value	n	Percent
Valid Values		Acceptable	828	71.4%
		Unacceptable	323	27.8%
Missing Values	System		9	0.8%

In general, a majority (n=828, 71.4%) of the respondents in the selected study area found the thermal environment to be acceptable while only 27.8% (n=323) found the thermal environment to be unacceptable. Ironically, a majority of the respondents accepted the thermal environment despite having about 73.8% (n=856) expressing positive thermal sensation as shown in Figure 4.11. Logically speaking, the respondents are expected to have a higher unacceptance rate as they claimed the environment to be warm and hot. This finding is found to be similar to the findings from (Chow et al., 2016; Nasir et al., 2013a).

One possible explanation could be associated with the very limited amount of control that one possesses towards the dynamic outdoor environment. Realizing this, respondents would choose to accept that there is nothing that could be done on an individual level which could contribute to the betterment of the thermal environment. As a consequence, the urban community would lower their expectation level and conclusively accept the thermal environment.

4.3.3.3 The thermal preference of urban community

The thermal preference is an indicator for the respondents to express their expectation on how the thermal environment should be. The thermal preference expressed through the McIntyre thermal preference scale is summarized in Table 4.14.

Table 4.14: Summary of thermal preference vote

		Value	n	Percent
Valid Values	-1	Warmer	114	9.8%
	0	No change	232	20.0%
	1	Cooler	806	69.5%
Missing Values	System		8	0.7%

In general, a majority (n=806, 69.5%) wanted a cooler environment as opposed to only 9.8% (n=114) who wanted a warmer environment. Meanwhile, 20.0% (n=232) of the respondents preferred the thermal environment as to how it is. The distribution of the thermal preference vote in the selected study area is shown in Figure 4.12.

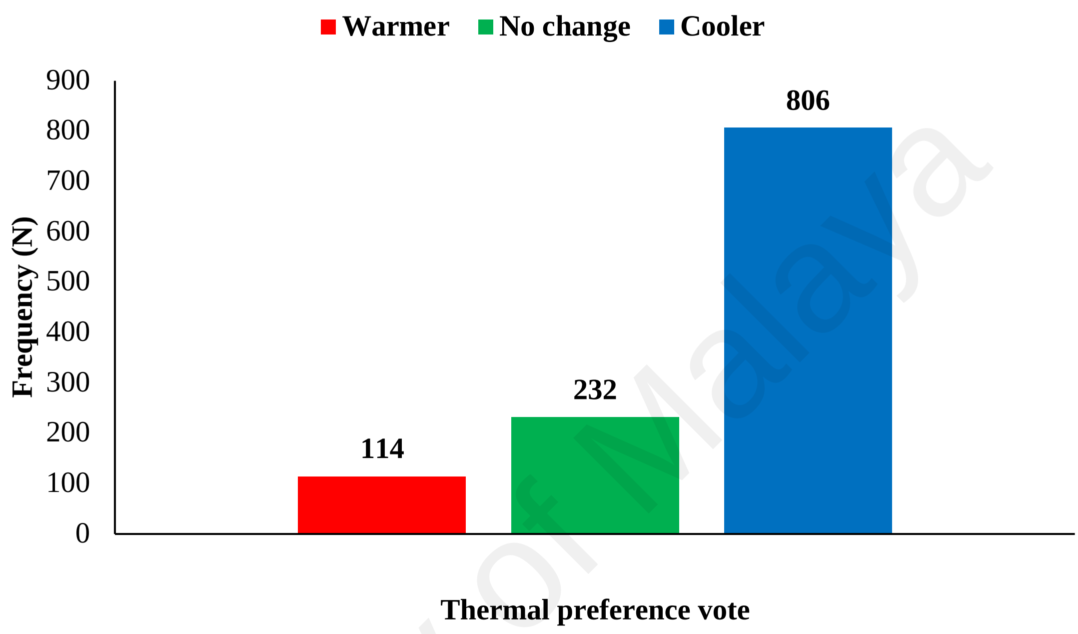


Figure 4.12: Thermal preference of the respondents

The thermal preference is found to be skewed negatively indicating a higher preference towards a cooler environment. This finding contradicts with the thermal acceptance votes while agreeing to the thermal sensation votes. The high votes in wanting a cooler environment is expected as a big majority (n=856, 73.8%) of the sample population were feeling warm and hot. On the contrary, the high acceptance vote (n=828, 71.4%) should reflect in a higher vote for no change to the environment, but instead, a majority (n=806, 69.5%) voted for a cooler environment. This finding supports the earlier finding where an individual will choose to accept the hotter environment because of the very limited amount of control they possess towards the dynamic outdoor environment. However, if they were given a choice, they would prefer a cooler environment instead. This recalls the importance of psychological OTC assessment on top of assessing the physiological heat stress as these key determining facts would be missed out and left unravelled by only assessing physiological OTC level.

4.3.3.4 The thermal comfort level of urban community

The thermal comfort is an indicator to describe the respondent's level of satisfaction towards the surrounding thermal environment in terms of comfort level. The thermal comfort vote is summarized in Table 4.15 below.

Table 4.15: Summary of thermal comfort level

		Value	n	Percent
Valid Values	-2	Very discomfort	76	6.6%
	-1	Little discomfort	560	48.3%
	0	No effect	229	19.7%
	1	Little comfort	236	20.3%
	2	Very comfort	55	4.7%
Missing Values	System		4	0.4%

In general, a majority (n=560, 48.3%) of the respondents reported experiencing little discomfort in the selected study area. In further analysis, the findings from thermal comfort level are dichotomised into thermal comfort (no effect, little comfort and very comfort) and thermal discomfort (very discomfort and little discomfort). It was found that 54.9% (n=636) of the sample population expressed thermal discomfort while the remaining 44.8% (n=520) were at a thermal comfort level. The analysis of the thermal discomfort group is summarized in Table 4.16.

Table 4.16: Summary of thermal discomfort according to time, gender, age and races (n=636)

Parameters		Thermal discomfort	
Time		**n**	**%**
	8 AM	86	13.5
	9 AM	46	7.2
	10 AM	21	3.3
	11 AM	26	4.1
	12 PM	35	5.5
	1 PM	71	11.2
	2 PM	105	16.5
	3 PM	102	16.0
	4 PM	47	7.4
	5 PM	45	7.1
	6 PM	21	3.3
	7 PM	30	4.7
	8 PM	1	0.2
Gender			
	Female	358	56.3
	Male	275	43.2
	Unwilling to disclose	3	0.5
Age			
	Young adults (< 18 years old)	122	19.2
	Adults (19 – 64 years old)	500	78.6
	Elderlies (> 65 years old)	3	0.5
	Unwilling to disclose	11	1.7
Races			
	Malay	247	38.8
	Chinese	267	42.0
	Indian	55	8.7
	Others	67	10.5

According to Table 4.16, a third (n=207, 32.5%) of the thermal discomfort was experienced between 2.00 to 3.00 pm. These responses can be anticipated because the urban environment in MJ is hottest around 2.00 pm with the average Ta recorded at 31.45°C, RH at 62.90% and SR at 619.01 W/m^2 as shown in Table 4.3. Meanwhile, the thermal discomfort by gender is quite equally distributed with 56.3% (n=358) females and 43.2% (n=275) males. In addition, 78.6% (n=500) of the respondents which reported thermal discomfort are adults and mainly consists of Malay (n=247, 38.8%) and Chinese (n=267, 42.0%) respondents. Unfortunately, the finding from this section was only able to indicate the level of thermal discomfort while the true impact towards the health and well-being remains ambiguous. In Section 4.4, the influence of urban heat on HRIs are further elaborated. In the following section, the diurnal variations in psychological OTC are presented.

4.3.4 Diurnal variations in outdoor thermal comfort level at Masjid Jamek

According to Ramakreshnan et al. (2019), the UHI intensity in GKL was found to vary between 8.00 am to 8.00 pm. Hence, to adjust to the variations in urban microclimate, the hourly variations in psychological OTC level within these periods are identified and presented in this sub-section.

4.3.4.1 Hourly variation in thermal sensation votes

The mean of thermal sensation votes (MTSV) was identified for each hour beginning from 8.00 am to 8.00 pm and presented in Figure 4.13. Positive thermal responses are represented by red bars while negative thermal responses are represented by blue bars.

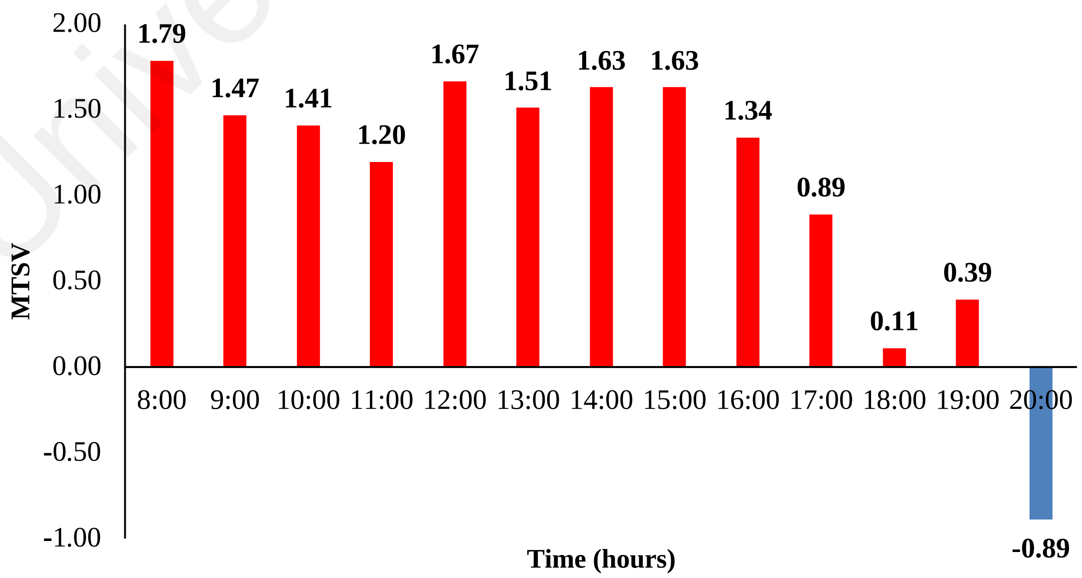


Figure 4.13: Hourly mean thermal sensation votes

As seen in Figure 4.13, 11 out of the 12 hours were represented with red bars with MTSV ranging between 0.11 to 1.79. Interestingly, the positive thermal responses started from 8.00 am up till 7.00 pm. Only after sunset at 7.00 pm, the MTSV of the respondents are found to fall within the category of negative thermal sensations. This finding is rather similar to the trends of sun sensation vote from Chow et al. (2016) which is conducted in one of the open spaces in Singapore. The presence of SR throughout the day is considered as a confounding factor for the people to feel hot at outdoor spaces. The study area which is located at a tropical region with rather high incoming SR ($\bar{x}$= 370.49 W/m^2, SD= 220.17 W/m^2) provides considerable urban heating occurrence that deteriorates MTSV and subsequently, the OTC level.

4.3.4.2 Hourly variation in thermal preference votes

In continuation, the mean of thermal preference vote (MTPV) was identified for each hour beginning from 8.00 am to 8.00 pm. The diurnal variations of MTPV are presented in Figure 4.14. The positive values of MTPV represent the preference of a cooler environment while the negative values of MTPV represent the preference of a warmer environment.

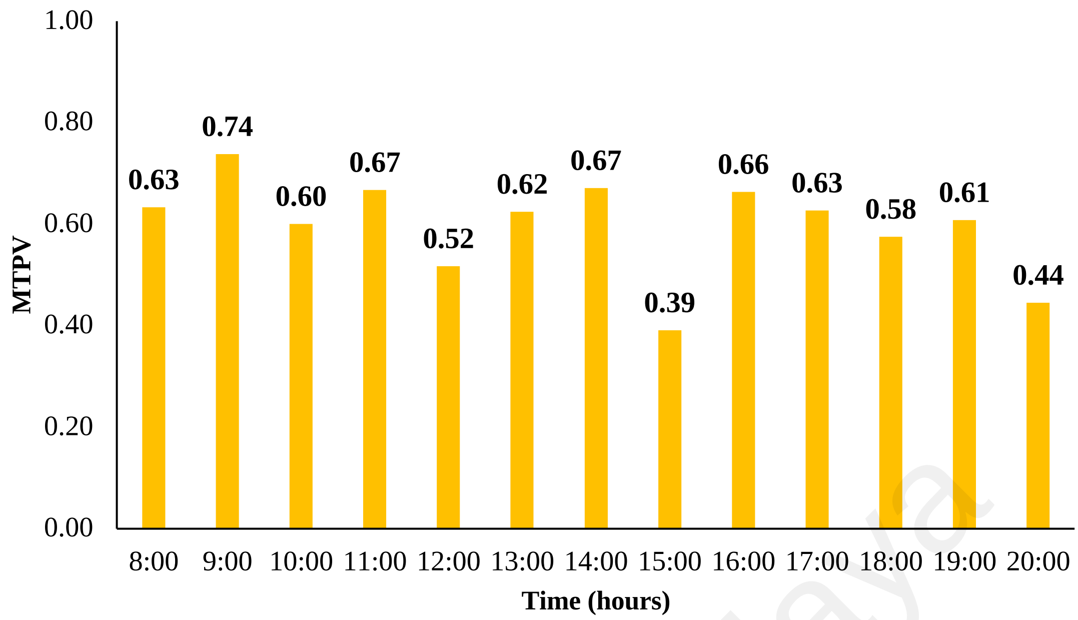


Figure 4.14: Hourly mean thermal preference votes

Figure 4.14 indicated that the preference towards a cooler environment (indicated by the positive MTPV ranging from 0.39 to 0.74) sustained from 8.00 am to 8.00 pm. Despite a change in MTSV at 7.00 pm as shown in Figure 4.13, the MTPV which remained positive shows that the respondents were expecting a cooler environment even after sunset. This finding is supporting evidence of the impact of UHI on the well-being of urban communities as the UHI intensity is found to be the most dominant few hours after sunset (Ramakreshnan et al., 2019). A cooler environment in the study area may be achievable through some mechanical cooling measures such as introducing a mist-spraying fan. Other urban heat mitigation measures such as introducing vegetation, replacing existing pavement with cooler materials, and other green sustainable solutions could be carried out to improve the urban thermal environment in the long run.

4.3.4.3 Hourly variations in thermal comfort levels

The hourly mean of thermal comfort votes (MTCV) was identified from 8.00 am to 8.00 pm to identify the variations of thermal comfort level in a diurnal manner. The diurnal variations of MTCV are presented in Figure 4.15. The thermal comfort level is represented by the positive value of MTCV while thermal discomfort level is represented by the negative value of MTCV.

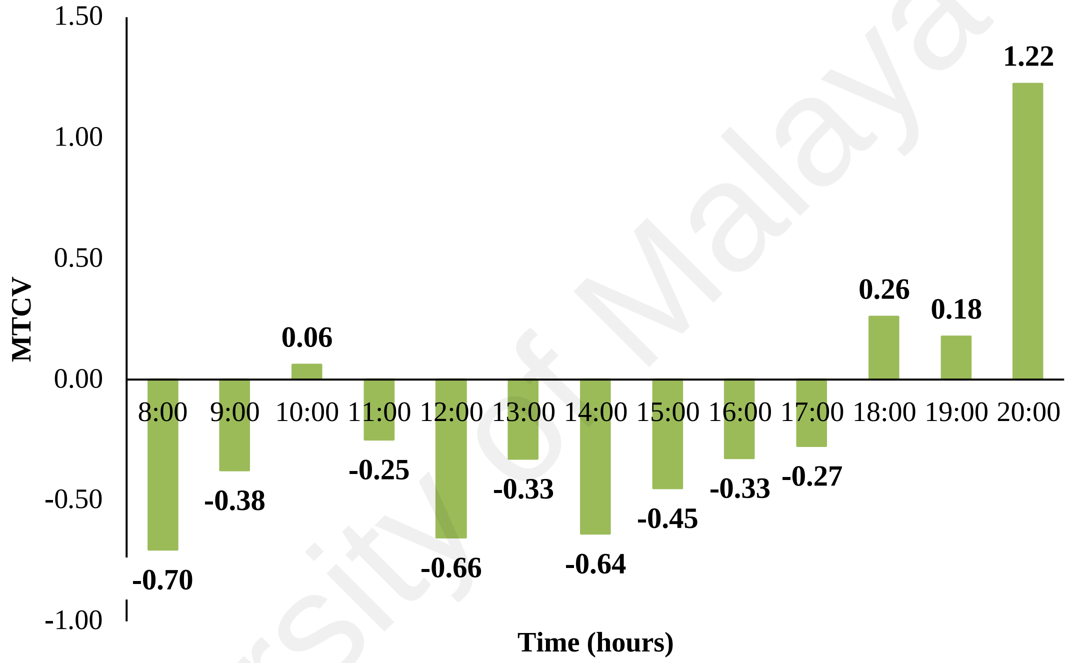


Figure 4.15: Hourly mean thermal comfort votes

The MTCV was found to fluctuate from -0.70 from 8.00 am to 1.22 from 8.00 pm. This indicates that the thermal discomfort occurs in the earlier period of the day from 8.00 am onwards and progressively improves after 2.00 pm. By comparing the variation in MTCV with the meteorological parameters from the AWS, it was observed that the MTCV is influenced by the diurnal variation in SR as shown in Figure 4.8. The thermal discomfort began around the same time at 8.00 am when the AWS started to record incoming SR. Similarly, the thermal discomfort began to improve gradually around 2.00

pm where the SR started to show reduction after peaking at 1:00 pm. As it approaches sunset around 7:00 pm where the SR is near to 0 W/m^2, the MTCV improves drastically to peak at 1.22 at 8.00 pm. Through this finding, it can be proposed that future urban design or urban heat mitigation measures should focus on shading mechanisms to ameliorate the heat entrapped and reduces direct exposure to sunlight which may cause thermal discomfort. For example, controlling the aspect ratio (height of building to the width of the road) within the city centre. On top of that, planting trees by roadsides is also deemed to be beneficial to the urban community in enhancing day to day OTC level.

4.3.5 The influence of duration of outdoor exposure on thermal sensation votes

The duration of outdoor exposure is a key component influencing the OTC level as well as the outcomes of HRIs. From Section 4.3.1, it was found that the respondents are spending about 6 hours on average (SD=4.0 hours) at outdoors in a day for various activities. In further analysis, the duration of outdoor exposure according to selected sociodemographic variables is identified and presented in the next sub-section.

4.3.5.1 Duration of outdoor exposure according to gender, age group and ethnicity

The duration of outdoor exposure according to selected sociodemographic variables such as gender, age group and ethnicity was identified. The summary of the duration of outdoor exposure is presented in Table 4.17.

Table 4.17: Duration of outdoor exposure in a day according to gender, age group and ethnicity

Sociodemographic variables	Mean (hours)	SD (hours)	n (%)
Gender			
Female	5.8	3.9	634 (54.7)
Male	6.4	4.1	523 (45.1)
Age group			
Young adults (< 18 years old)	6.6	3.7	191 (16.5)
Adults (19 – 64 years old)	6.0	4.0	948 (81.7)
Elderlies (> 65 years old)	3.9	2.5	7 (0.6)
Ethnicity			
Malay	6.2	4.3	511 (44.1)
Chinese	5.8	3.6	436 (37.6)
Indian	5.9	4.1	81 (6.9)
Others	7.2	4.0	132 (11.4)

According to Table 4.17, males generally spend longer hours outdoors with an average of 6.4 hours (SD=4.1 hours) as compared to females which spend an average of 5.8 hours (SD=3.9 hours). In terms of age group, it was found that young adults and adults are spending an average of 6.6 hours (SD=3.7 hours) and 6.0 hours (SD=4.0 hours) at outdoors, respectively. Meanwhile, the elderlies are found to spend only an average of 3.9 hours (SD=2.5 hours) at outdoors daily. In terms of ethnicity, it was found that the Malay, Chinese and Indian are spending about 6 hours in average at outdoors daily, while other ethnicities are spending about an hour more, i.e., 7.2 hours (SD=4.0 hours).

The difference in outdoor exposure across the various sociodemographic variables can be attributed to the nature of the working environment. However, these deductions are mainly based on observations because the questionnaire failed to record specific job descriptions of each respondent. Nevertheless, further analysis was conducted to identify the significance in the duration of outdoor exposure towards the outcome of OTC level. For that purpose, the duration of outdoor exposure was compared to MTSV. Table 4.18 is the summary of duration of exposure with their respective MTSV.

Table 4.18: Summary of mean thermal sensation votes by the duration of exposure

Duration of exposure (hours)	MTSV	n	Delta MTSV
< 3	1.3	239	-0.1
3 to 5	1.3	258	0.2
5 to 9	1.5	355	-0.1
> 9	1.4	255	

Kruskal_wallis H test shows that the MTSV was not statistically different ($p>0.05$) for the respondents with different exposure time. This indicates that the duration of exposure may not significantly influence the thermal sensation in the study area, although there is a change in MTSV across the different duration of exposure. Through thermoregulation mechanism, the human body requires time to adjust to the changing thermal environment. Pro-long exposure is one of the factors affecting the acclimatization of a person towards the hot environment.

On a side note, since each respondent were sampled on a period of about 10 minutes (the average time to complete the questionnaire), the current study cannot reflect the effect of changing climatic conditions towards thermal sensation. Therefore, as suggested by Cheng et al. (2012), the large sample size was included in different climatic conditions to offset the aforementioned effect towards the thermal sensation in the selected study area (Cheng et al., 2012). In other circumstances, a longitudinal approach of OTC studies could provide the observations to better understand the changes in thermal sensation over different climatic conditions (Cheng et al., 2012). Next, the coherence between the physiological and psychological OTC is discussed.

4.3.6 Coherence of physiological and psychological outdoor thermal comfort level

The OTC indices are a physiological indicator that models the thermal conditions of respondents while TSV obtained from the survey questionnaire are psychological indicators to understand the perceived thermal environment. The comparison of both physiological and psychological OTC is a form of validation to ensure the coherence in explaining how the body feels against what the mind perceives of the thermal environment. A Pearson product-moment correlation coefficient analysis is conducted to elucidate the strength of the relationship between physiological and psychological OTC. Preliminary analyses were performed to ensure no violation of the assumptions of normality, linearity and homoscedasticity. The descriptive statistics of the selected OTC indices and TSV are presented in Table 4.19.

Table 4.19: Descriptive statistics of selected outdoor thermal comfort indices and thermal sensation vote

	Mean	Std. Deviation	n
Physiological			
PET	29.45	2.106	864
PMV	1.59	0.669	864
SET	26.69	2.615	864
UTCI	32.41	2.215	501
WBGT	26.46	1.292	864
Psychological			
TSV	1.30	1.336	851

Meanwhile, the findings from correlation analysis are summarized in Table 4.20.

Table 4.20: Pearson correlation of thermal sensation vote with selected outdoor thermal comfort indices

		PET	PMV	SET	UTCI	WBGT
TSV	Correlation	-0.026	0.124**	-0.130**	0.079	0.102**
	n	851	851	851	490	851

** Correlation is significant at the 0.01 level (2-tailed).

From the correlation analysis in Table 4.20, there is a weak correlation between the TSV which represents the psychological OTC with the five selected OTC indices which represents the physiological OTC. TSV is found to be weakly correlated with PET (r=-0.026, n=851, p<0.01), PMV (r=0.124, n=851, p<0.01), SET (r=-0.130, n=851, p<0.01), UTCI (r=0.079, n=490, p<0.0.) and WBGT (r=0.102, n=851, p<0.0.1). Similar with the findings from Nasir et al. (2013), Chow et al. (2016), Din et al. (2014) and Nasir et al. (2012), the findings from this study shows that the subjective response doesn't coincide well with the measured value of thermal comfort indices.

The inconsistency between the objective and subjective measurements is observed in many OTC studies because of the complex bio-meteorology interaction (Makaremi et al., 2012; Nikolopoulou & Steemers, 2003). Due to the complexity of thermal comfort involving the unpredictable aspects of the physiological and psychological response of a person, the heat balance of the human body (although it is well-developed based on extensive knowledge in human physiology and heat transfer theory) cannot fully explain the thermal perceptions and preferences in different urban outdoor environments (Hoppe, 2002; Nikolopoulou et al., 2001). Hence, the subjective assessment is important not only to validate the application of various OTC indices in the different urban thermal environment but also to explore underlying issues that cannot be reflected through the indices. In the next section, the findings on psychological OTC expressed as the physiological equivalent temperature is presented.

4.3.7 Expressing psychological outdoor thermal comfort via physiological equivalent temperature

4.3.7.1 The expected neutral temperature of the urban community in study area

To identify the temperature where the urban community would feel neutral, the PET index representing physiological OTC is divided into a total of 22 bins with an increment of 0.5°C PET. Then, the MTSV is identified in each corresponding bin. The linear regression of MTSV against PET as shown in Figure 4.16 was used to identify the intersection at MTSV=0.

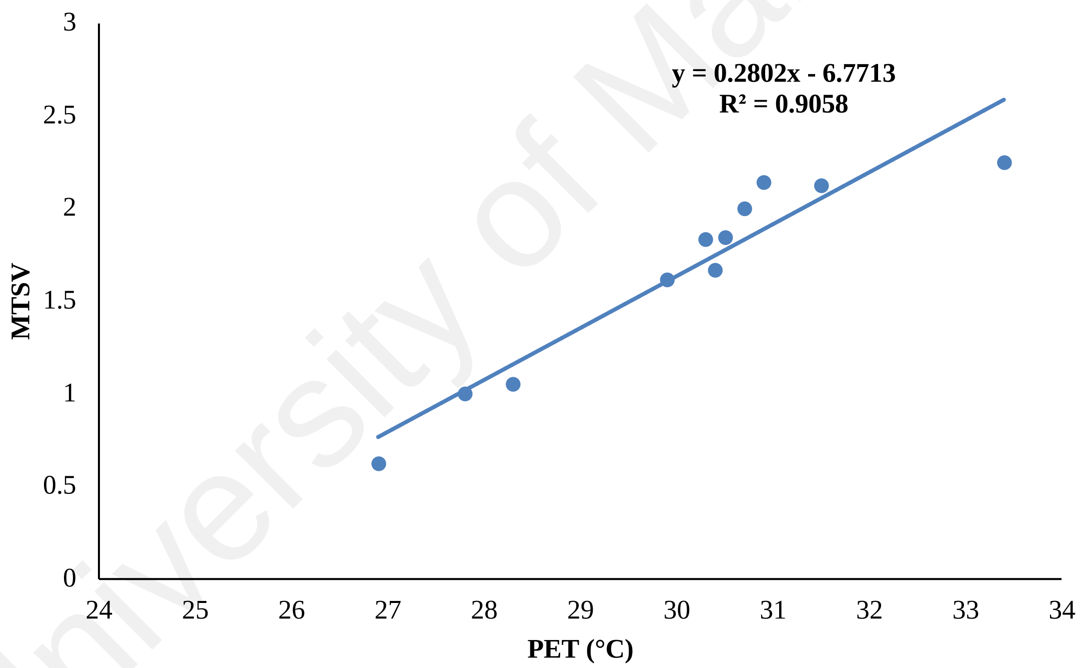


Figure 4.16: Identifying the neutral temperature of the urban community in study area

The linear equation from the association of MTSV and PET is as shown below:

$$MTSV = 0.2802PET - 6.7713, R^2 = 0.9058 \quad \text{(Eq. 11)}$$

According to the linear equation, by solving for MTSV=0 for neutral TSV, the urban community expresses neutral thermal sensation at 24.17°C PET. Besides that, each change of vote from a thermal sensation class to another was characterized by a difference of 4°C PET. Hence, an improvement of 4°C PET to the urban environment will be able to cause a shift in the thermal sensation. For example, from “very hot” to “hot”, “slightly warm” to “neutral” and so on.

4.3.7.2 The acceptable range of temperature of the urban community in study area

To identify the acceptable range of temperature of the urban community in the study area, the probability of the urban community not accepting the thermal environment is plotted against PET as shown in Figure 4.17. The intersection line of y=0.3 is chosen to identify the acceptable range of temperature for at least 70% of the population in the study area.

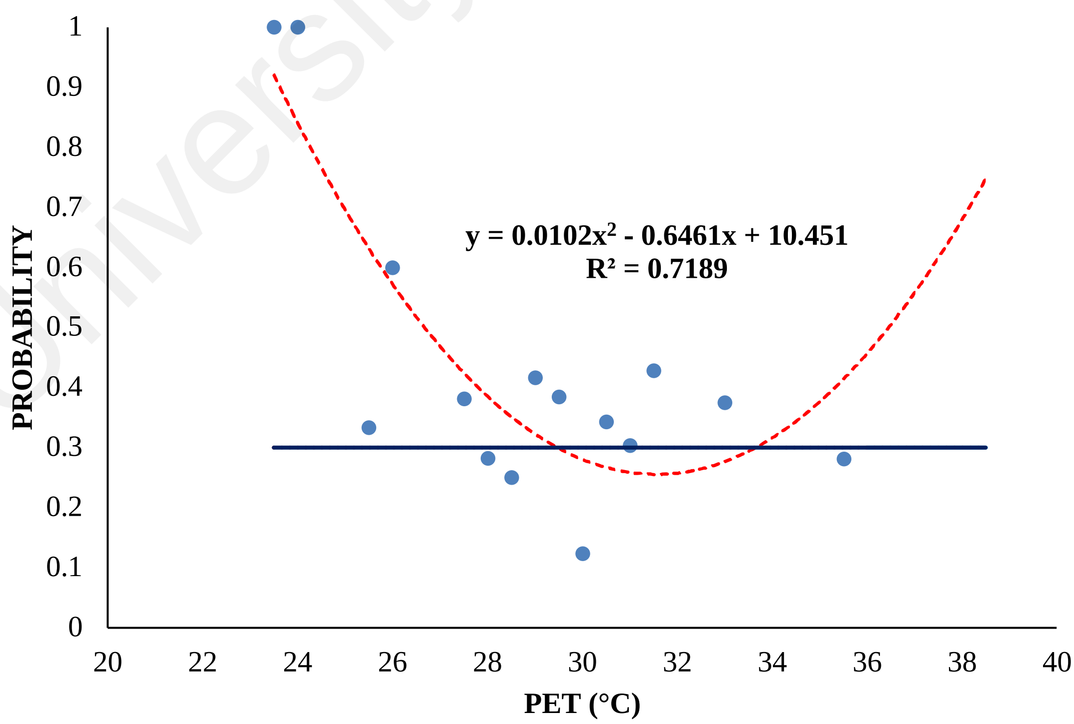


Figure 4.17: The acceptable range of temperature for the urban community

The second-degree polynomial function that represents the probability of thermal acceptance is expressed as follow:

$$y = 0.0102x2 - 0.6461x + 10.451, R^2 = 0.7189 \qquad \text{(Eq. 12)}$$

By solving the equation for y=0.3 representing thermal acceptability of 70%, the acceptable range of temperature for the urban community is 28.86 to 34.48 °C PET. The percentage of respondents thermally accepts an environment, i.e., do not express dissatisfaction, is lowered to 70% as compared to the 80% as outlined in ASHRAE 55 because it is reasonable to account for the microclimate fluctuations in the dynamic outdoor environment. Albeit the reduction, the 70% will still be able to represent the majority by covering more than two-thirds of total occupants (Bakar & Gadi, 2016). In a tropical region, lowering the percentage of thermal acceptance is justified as people from this region are more adapted to the hot-humid climate all year round.

4.3.7.3 The preferred temperature of the urban community in study area

Probit analysis is conducted to identify the preferred temperature of the urban community in the study area. The preferred temperature is identified as the temperature where individuals do not prefer either a cooler or warmer thermal environment. The two log-linear functions representing the preference of cooler and warmer temperature is depicted in Figure 4.18.

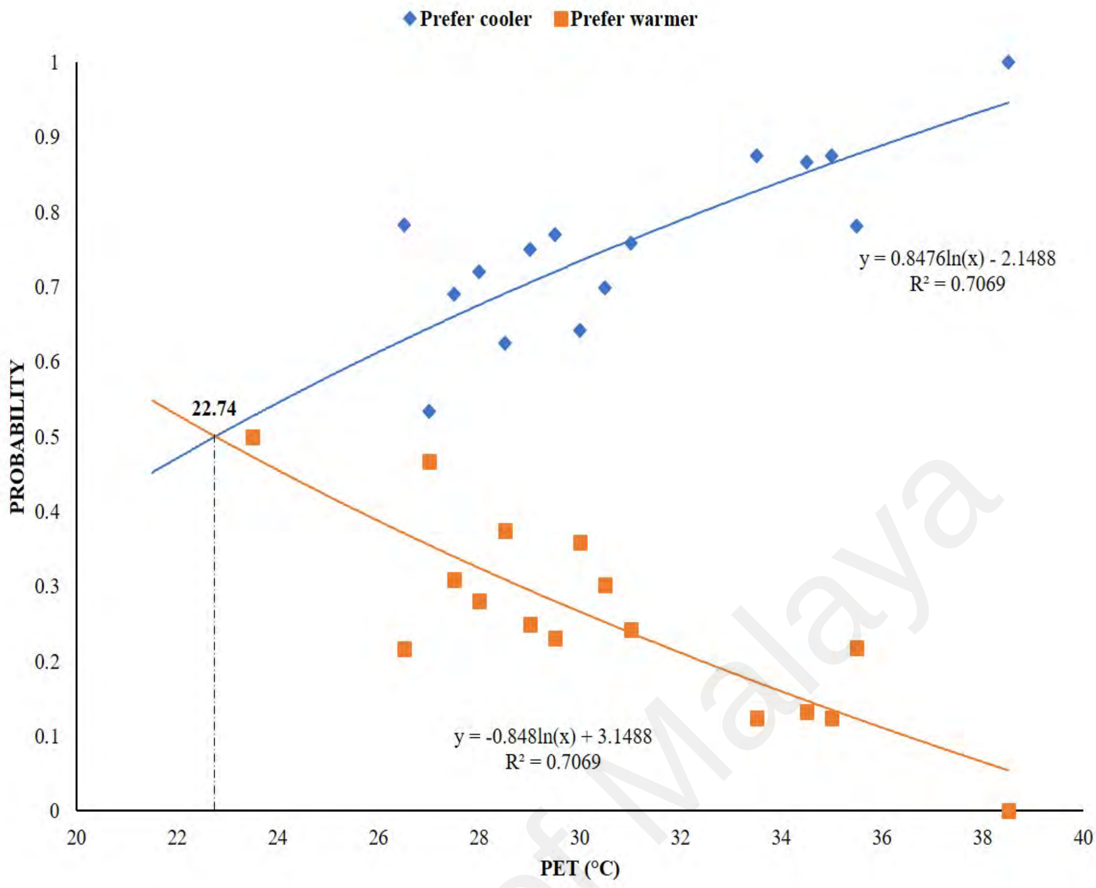


Figure 4.18: The preferred temperature of the urban community

The log-linear function which represents the urban community preferring a cooler environment is expressed as:

$$y = 0.8476\ln(x) - 2.1488, R^2 = 0.7069 \qquad \text{(Eq. 13)}$$

Meanwhile, the log-linear function which represents the urban community preferring a warmer environment is expressed as:

$$y = -0.848\ln(x) + 3.1488, R^2 = 0.7069 \qquad \text{(Eq. 14)}$$

The intersection of the two log-linear functions revealed that the preferred temperature of the urban community is 22.74°C PET. On a side note, it is important to highlight the difference between thermal sensation and thermal preference because sensation refers to the immediate influence of climatic parameters on the individual while the latter refers to the desired conditions or expectation on how the climatic parameters should be (Makaremi et al., 2012).

4.3.7.4 The physiological equivalent temperature to express thermal comfort in the study area

The mean of thermal comfort votes (MTCV) is identified and binned with an increment of 0.5°C PET to identify the temperature where the urban community would attain thermal comfort. The linear regression of MTCV against PET is used to identify the intersection at MTCV=0, i.e., the PET for an individual to report thermal comfort or discomfort is shown in Figure 4.19.

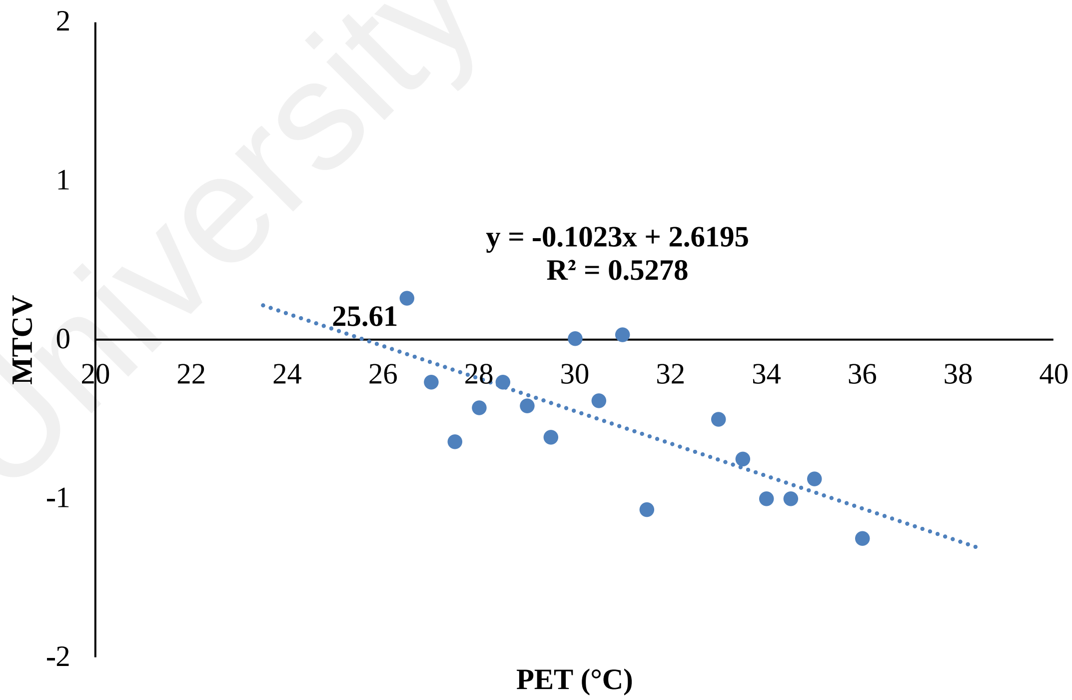


Figure 4.19: The physiological equivalent temperature for the urban community to express thermal comfort

The linear regression that expresses the thermal comfort as a function of PET is as shown below:

$$y = -0.1023x + 2.6195, R^2 = 0.5278 \quad \text{(Eq. 15)}$$

By solving for y=0, the PET for an individual to express thermal comfort or discomfort is 25.61°C PET.

4.3.8 Traits of thermal adaptation among urban communities in study area

Table 4.21 is a summary of findings from Section 4.3.7 which express the psychological OTC level in physiological equivalent temperature.

Table 4.21: Summary of outdoor thermal comfort findings in the study area

Heat-stress indicator	Reference temperature (°C PET)
Temperature to feel neutral at outdoors	24.17
Acceptable range of temperature at outdoors	28.86-34.48
Preferred temperature at outdoors	22.74
Cut-off point to express thermal comfort/discomfort at outdoors	25.61

A respondent showed trait of adaptive thermal comfort when they perceived the environment to be better as compared to measured microclimate conditions (Nasir et al., 2012). For example, findings revealed that the acceptable range of temperature at outdoors was higher between 28.86 to 34.48°C PET as compared to the preferred temperature of the urban community in the study area which is 22.74°C PET. In a similar study in Singapore, the vote of thermal acceptability and overall comfort condition contradicts with reported high values of OTC indices which exceeds thresholds (Chow et al., 2016).

Adaptation is practised (either consciously or subconsciously) at an individual level as an alternative to mitigation measures towards the hot and humid outdoor environments. The adaptation to thermal comfort can either be a physical and/or physiological process (Huizenga et al., 2001; Sanesi et al., 2006) distinguished according to three categories, i.e., behavioural (personal, environmental, technological or cultural), physiological (genetic adaptation or acclimatization) and psychological (habituation and expectation) (Brager & de Dear, 1998; Yang et al., 2013). Besides that, thermal environment history which comprises of cultural background, experience, the expectation of thermal environment, active body heat control and exposure time can also directly influence the adaptation of a person towards the thermal environment (Fong et al., 2020; Kurazumi et al., 2016).

4.3.9 A proposed heat stress guideline for a tropical city

The occurrence of heat stress is one of the findings commonly emphasized in OTC studies as it directly affects the well-being of urban communities. A heat stress guideline shown in Table 4.22 is proposed for a tropical city based on the earlier findings from Section 4.3.7. The heat-stress guideline adopted the modified ASHRAE scale as it could better represent the thermal expression in a tropical climate. The neutral temperature which is approximately 24°C PET is chosen as the mid-point separating the hot and cold sensation in the heat stress guideline. According to Eq. 11, each change of thermal sensation vote is characterized by a difference of 4°C PET. Hence, this finding is applied to define the range of temperature in this proposed heat stress guideline.

Table 4.22: Proposed heat-stress guideline for a tropical city

Thermal sensation	Reference temperature (°C PET)
Very hot	>36
Hot	32-36
Slightly warm	28-32
Neutral	24-28
Slightly cool	20-24
Cold	16-20
Very cold	<16

Few studies have addressed the considerable influence of UHI in aggravating extreme weather events (Emmanuel & Krüger, 2012; Ramamurthy & Sangobanwo, 2016) such as heat waves (Zhao et al., 2018) and inducing outdoor thermal discomfort (Qaid et al., 2016; Taleghani & Berardi, 2018). In their critical appraisal, Fong et al. (2019) highlighted the lack of a heat stress guideline relatable up to the extent of expressing bio-physiological and thermoregulation stress in a human body in the tropical region of South East Asia. This prevents the effective communication of extreme weather events that are occurring more frequently in the past few years. On top of that, the approach of merely depending only on one parameter such as Ta to express heat stress level is criticized for being insufficient (Chow et al., 2016).

As such, the heat stress guideline as proposed through this study have two advantages. Firstly, it is easily evaluated through open-source software (RayMan Pro) with commonly found meteorological parameters. This would allow the guideline to express the physiological equivalent heat stress on the human body which is based on validated findings from this research. Secondly, it is expressed in a commonly known unit (°C PET) that could be easily understood by any layperson. This heat stress guideline could be implemented by the government and other relevant agencies in a tropical climate to monitor heat exposure in an urban environment. On top of that, the relevant authorities can also prepare counter-measures such as intervention and mitigation initiatives to ensure the liveability and well-being of the urban communities is on a non-threatening level. In short, the guideline will be beneficial to support the decision-making mechanism.

4.3.10 Summary

In summary, an adaptive approach was used to evaluate the OTC level of urban communities in MJ. The microclimate data from the AWS is used to evaluate the physiological OTC indices while a large-scale questionnaire survey is conducted to evaluate the psychological OTC thermal responses. Among the five selected OTC indices, PET is chosen to represent physiological OTC. In general, the urban communities are expected to experience slight physiological heat stress with an average of 29.45°C PET (SD=2.11°C PET). The findings from physiological OTC indicated that only 37.2% (n=321) reported positive thermal sensation. In further analysis, the findings from physiological OTC was found to contradict with the findings from psychological OTC where 73.8% (n=856) of the respondents reported positive thermal sensation. Results from 1160 eligible respondents also indicated a majority (n=806, 69.5%) wanted a cooler environment despite having 71.4% (n=828) of the respondents expressing thermal acceptance. Lastly, it was found that only 44.8% (n=520) of the urban communities were at thermal comfort level while the others expressed thermal discomfort. The association of OTC with selected sociodemographic variables revealed ethnicity (p=0.002) to be significantly associated with expressing thermal response while gender (p=0.670), age group (p=0.113) and duration spent outdoors in a day (p=0.814) were not significantly associated.

In terms of diurnal variation in OTC, the MTSV of the respondents are found to fall within the category of positive thermal response 11 out of the 12 hours from sunrise at

8.00 am to sunset at 7.00 pm. The preference towards a cooler environment was found to sustain from 8.00 am to 8.00 pm despite a change in MTSV at 7.00 pm. The MTPV which remained positive shows that the respondents were expecting a cooler environment even after sunset. In terms of thermal comfort level, the MTCV was influenced to a certain extent by the variation in SR.

By expressing psychological OTC via PET, it was found that the urban community expresses neutral thermal sensation at 24.17°C PET, while the acceptable range of temperature for at least 70% of the population in the study area is 28.86 to 34.48°C PET. The preferred temperature of the urban community is 22.74°C PET. Meanwhile, the temperature for an individual to express thermal comfort/discomfort is 25.61°C PET. Respondents in this study were found to exhibit traits of adaptive thermal comfort when they perceived the environment to be better as compared to measured microclimate conditions.

A heat stress guideline is proposed for a tropical city. The proposed heat stress guideline has two advantages. Firstly, it is easily evaluated through open-source software (RayMan Pro) with commonly found meteorological parameters. Secondly, it is expressed in a commonly known unit (°C PET) that could be easily understood by any layperson. In future, more effort and studies are needed to promote and identify its practicability among other relevant stakeholders.

4.4 Phase 2: The impact of urban heat on the health and well-being of urban community

The findings from the large-scale questionnaire survey related to HRIs is presented in this section. Despite careful implementation of the survey, there was missing information especially on heat-related symptoms. To ensure relevant findings, “Exclude cases listwise” was chosen during data analyses. This explains the varying number of participants in various analysis in Section 4.4. The health impact from urban heat exposure is classified according to their symptom types which are physical, psychosomatic and psychological. Therefore, the sub-sections are broken down following the three types of health impact and elaborated in the following sections.

4.4.1 Prevalence of physical symptoms from heat exposure

Physical health is important to ensure overall well-being and is defined as the condition of the body expressing one’s fitness level (European Patients’ Academy, 2015). Through the questionnaire survey, the commonly reported physical symptoms from heat exposure are summarized in Table 4.23.

Table 4.23: Summary of reported physical symptoms from heat exposure

Ranking according to most reported symptoms	Symptoms	Frequency (%) (n=1160)
1	Heat exhaustion	569 (49.1)
2	Throat irritation	525 (45.3)
3	Eyes irritation	406 (35.0)
4	Skin itchiness	350 (30.2)
5	Difficulties in eyesight	348 (30.0)
6	Difficulties in breathing	338 (29.1)
7	Heatstroke	309 (26.6)
8	Heat cramps	292 (25.2)
9	Physical eye pain	243 (20.9)
10	Difficulties in hearing	129 (11.1)

Heat exhaustion was found to be the most reported symptoms with about half (n=569, 49.1%) of the respondents reported of experiencing it. Other physical symptoms such as throat irritation (n=525, 45.3%), eyes irritation (n=406, 35.0%), skin itchiness (n=350, 30.2%), and difficulties with eyesight (n=348, 30.0%) are among the top 5 reported symptoms. Meanwhile, other symptoms were found to have less impact on the physical health of the urban communities in the study area. Further analysis was conducted to identify the prevalence of physical health symptoms according to selected sociodemographic indicators. The findings are presented in the following sub-section.

4.4.1.1 Physical health impact score

The prevalence of physical health symptoms for each respondent was identified via their individual physical health impact scores. The mean and standard deviation of overall physical health impact scores are summarized in Table 4.24.

Table 4.24: The mean and standard deviation of physical health impact score

Variables	Participants (n = 1104)	Impact Score	95% CI	
	n (%)	Mean ± SD	Lower	Upper
Physical Health Impact Score				
Scores 5 - 9	285 (25.8)	6.14 ± 1.27	6.00	6.29
Scores 0 - 4	819 (74.2)	1.96 ± 1.38	1.87	2.06

In general, a majority (n=819, 74.2%) were found to have low physical health impact scores with a mean of 1.96 (SD=1.38) and only 25.8% (n=285) of the respondents were having high physical health impact scores with a mean score of 6.14 (SD=1.27). In subsequent data analysis, univariate analysis was conducted for the physical health impact score with selected sociodemographic indicators.

4.4.1.2 Factors influencing severity of physical symptoms

The findings from the univariate analysis are summarized in Table 4.25. Urban communities that were more likely to report high physical impact scores are found to be female (n=174, 15.8%), less than 20 years old (n=90, 8.2%), Malay (n=142, 13.2%), spent 3 to 5 hours a day at outdoors (n=88, 8.2%) and reporting positive thermal response (n=128, 15.7%). However, the univariate analysis revealed that the physical health impact score was only significantly associated with gender (p=0.023) and ethnicity (p<0.001). Meanwhile, age group (p=0.273), duration spent outdoors in a day (p=0.162) and PET (p=0.399) were not significantly associated.

Females are found to be about 30% less likely to express physical health symptoms as compared to males (OR=0.73, 95% CI: 0.55-0.96). The difference in expressing physical health symptoms may be attributed to how males and females experience bodily distress

(Barsky, Peekna, & Borus, 2001). Besides that, the duration spent outdoors in a day was also found to be different according to gender as shown in Table 4.17. Female's average outdoor exposure in a day is found to be 5.8 hours (SD=3.9 hours) which is lesser as compared to male's average outdoor exposure in a day at 6.4 hours (SD=4.1 hours).

On the other hand, the likelihood of expressing physical health symptoms is 283%, 61% and 0.4% for Indians (OR=2.83, 95% CI: 1.42-5.65), Malay (OR=1.61, 95% CI: 0.94-2.75) and Chinese (OR=1.04, 95% CI: 0.60-1.81) respectively, as compared to other ethnicities. There could be a few plausible explanations for this finding. Similarly, the duration of outdoor exposure can also be one of the influencing factors as the average duration of exposure across the ethnicities was found to be different in Table 4.17. The Chinese spent the least hours at outdoor spaces in a day with an average of 5.8 hours (SD=3.6 hours) while other ethnicities were found to be spending 5.9 to 7.2 hours on average per day. This observation may be associated with the nature of their respective working environment. For example, hawkers spent a great amount of time at outdoor spaces selling food and beverage to by-passer from early morning till late evening. In the study area, the hawker respondents were mostly non-Chinese. Unfortunately, these deductions were merely plain observations because the large-scale questionnaire failed to record specific job descriptions of each respondent.

Table 4.25: Univariate analysis of physical health impact score according to selected sociodemographic

Variables	Participants	Physical Health Impact Score		OR (95% CI)	p-value
		Scores 5 - 9	Scores 0 - 4		
Gender (n = 1104)					**0.023***
Male	494 (44.7)	111 (10.1)	383 (34.7)	0.73 (0.55, 0.96)	
Female	610 (55.3)	174 (15.8)	436 (39.5)	Reference	
Age group (n = 1093)					**0.273**
< 20 years	357 (32.7)	90 (8.2)	267 (24.4)	0.83 (0.58, 1.20)	
20 -23 years	218 (19.9)	46 (4.2)	172 (15.7)	0.66 (0.43, 1.01)	
24 - 31 years	268 (24.5)	72 (6.6)	196 (17.9)	0.91 (0.62, 1.33)	
> 31 years	250 (22.9)	72 (6.6)	178 (16.3)	Reference	
Ethnicity (n = 1078)					**<0.001***
Malay	496 (46.0)	142 (13.2)	354 (32.8)	1.61 (0.94, 2.75)	
Chinese	417 (38.7)	86 (8.0)	331 (30.7)	1.04 (0.60, 1.81)	
Indian	70 (6.5)	29 (2.7)	41 (3.8)	2.83 (1.42, 5.65)	
Others	95 (8.8)	19 (1.8)	76 (7.1)	Reference	
Duration spent outdoors in a day (n = 1068)					**0.162**
< 3 hours	229 (21.4)	49 (4.6)	180 (16.9)	0.76 (0.50, 1.16)	
3 - 5 hours	342 (32.0)	88 (8.2)	254 (23.8)	0.97 (0.67, 1.41)	
5 - 9 hours	242 (22.7)	74 (6.9)	168 (15.7)	1.24 (0.84, 1.83)	
> 9 hours	255 (23.9)	67 (6.3)	188 (17.6)	Reference	
Physiological Equivalent Temperature (n = 816)					**0.399**
Positive Thermal Response	510 (62.5)	128 (15.7)	382 (46.8)	1.15 (0.83, 1.58)	
Neutral and Negative Thermal Response	306 (37.5)	85 (10.4)	221 (27.1)	Reference	

Secondly, it was observed that the respondents in the study area are wearing different attires as an influence of ethnicity and religion. For example, Malay females are commonly found to be wearing a headscarf covering their hair to the chest because of their religious needs. The others may not follow this because of the multi-ethnic background. It is inferred that the more clothing layer on a person will influence their thermoregulation system which subsequently affects their heat perception and the outcome of the physical health symptoms reported. Similarly, these deductions will require more in-depth study to unravel the influence of ethnicity towards OTC level and physical health symptoms reported. Next, the 9 items under the physical health symptoms are clustered into respective components via EFA and presented in the next sub-section. The Chinese spent the least hours at outdoor spaces in a day with an average of 5.8 hours (SD=3.6 hours) while other ethnicities were found to be spending 5.9 to 7.2 hours on average per day. This observation may be associated with the nature of their respective working environment. For example, hawkers spent a great amount of time at outdoor spaces selling food and beverage to by-passer from early morning till late evening. In the study area, the hawker respondents were mostly non-Chinese. Unfortunately, these deductions were merely plain observations because the large-scale questionnaire failed to record specific job descriptions of each respondent.

4.4.1.3 Components of physical health symptoms

Through EFA, 9 items under the physical health symptoms are loaded into two components which were then classified as symptoms related to sensory organ pain and heat-related illnesses. The sensory organ pain is related to the reflex and response of an individual while the heat-related illnesses are related to the psychomotor of an individual when exposed to heat. Table 4.26 summarizes the physical symptoms according to each component.

Table 4.26: Physical symptoms according to the components generated through Exploratory Factor Analysis

Components	Sensory organ pain	Heat-related illnesses
Symptoms	Irritation of eyes	Heat exhaustion
	Difficulties in vision or limited eyesight	Heat cramps
	Physical pain in both eyes	Heat stroke
	Irritation of throat	Skin itchiness
	Difficulties in breathing	

The association of PET with each component of the physical symptoms were performed to identify the influence of sociodemographic indicators as confounding factors. The association of physical health components with PET according to the sociodemographic is summarized in Table 4.27.

Table 4.27: Physical health components according to sociodemographic

Variables	Participants	Physical health subscale	
		Sensory organ pain (5 items)	**Heat-related illnesses (4 items)**
	n (%)	**Median score (IQR)**	
Gender (n = 1104)			
Male	494 (44.7)	1.00 (2.00)	1.00 (2.00)
Female	610 (55.3)	2.00 (3.00)	1.00 (2.00)
p value		**0.013***	**0.199**
Age group (n = 1093)			
< 20 years	357 (32.7)	2.00 (2.00)	1.00 (2.00)
20 -23 years	218 (19.9)	1.00 (2.00)	1.00 (2.00)
24 - 31 years	268 (24.5)	1.00 (3.00)	1.00 (2.00)
> 31 years	250 (22.9)	1.00 (3.00)	1.00 (3.00)
p value		**0.023***	**0.028***
Ethnicity (n = 1078)			
Malay	496 (46.0)	1.00 (2.75)	1.00 (3.00)
Chinese	417 (38.7)	1.00 (3.00)	1.00 (2.00)
Indian	70 (6.5)	2.00 (3.00)	1.00 (2.00)
Others	95 (8.8)	1.00 (3.00)	1.00 (2.00)
p value		**0.005***	**<0.001***
Duration spent outdoors in a day (n = 1068)			
< 3 hours	229 (21.4)	1.00 (2.00)	1.00 (2.00)
3 - 5 hours	342 (32.0)	2.00 (3.00)	1.00 (2.00)
5 - 9 hours	242 (22.7)	1.00 (3.00)	1.00 (2.00)
> 9 hours	255 (23.9)	2.00 (3.00)	1.00 (2.00)
p value		**0.015***	**0.683**
Physiological Equivalent Temperature (n = 816)			
Positive Thermal Response	510 (62.5)	2.00 (2.00)	1.00 (2.00)
Neutral and Negative Thermal Response	306 (37.5)	1.00 (3.00)	1.00 (2.00)
p value		**0.101**	**0.859**

According to Table 4.27, PET was found to be not significantly associated with sensory organ pain and heat-related illnesses. Through this finding, it is postulated that the thermal environment has less influence on the sensory response of an individual at urban outdoor spaces. Although heat-related illnesses were also found to be not significantly associated, there are reasons to believe otherwise. This finding is unexpected because it contradicts with the norm of heat-related symptoms. Under the presence of heat stress, the human thermoregulation system would require immense energy for heat exchange processes such as sweating. Hence, an individual is expected to experience heat exhaustion or heat cramps after prolong exposure in a hot ambient environment (Centers of Disease Control and Prevention, 2017).

One possible reason for the insignificant association could lie in the perceived severity of the respective symptoms. In a tropical city, the people are acclimatized with the constant hot and humid environment and experienced fatigue regularly throughout the year. Therefore, symptoms such as heat stroke and heat exhaustion could be perceived to be on a higher level of severity as compared to fatigue. A more in-depth study on the influence of the thermal environment in a tropical climate towards the physical health outcome should be carried out in the future. Meanwhile, the prevalence of psychosomatic symptoms as related to urban heat exposure is presented in the next section.

4.4.2 Prevalence of psychosomatic symptoms from heat exposure

Through the questionnaire survey, the commonly reported psychosomatic symptoms from heat exposure are summarized in Table 4.28.

Table 4.28: Summary of reported psychosomatic symptoms from heat exposure

Rank according to most reported symptoms	Symptoms	Frequency (%) (n=1160)
1	Tiredness	891 (77.0)
2	Trouble sleeping	769 (66.5)
3	Headaches	684 (59.1)
4	Dizziness	538 (46.5)
5	Pain in arms, legs or joints	493 (42.6)
6	Back pain	426 (36.8)
7	Constipation or diarrhoea	292 (25.2)
8	Nausea, gas or indigestion	292 (25.2)
9	Irregular heartbeat	368 (31.8)
10	Shortness of breath	362 (31.3)
11	Fainting spells	276 (23.9)
12	Stomach pain	392 (33.9)
13	Chest pain	273 (23.6)
14	Menstrual cramps or period problems	288 (45.4)*

*Only accounts for the female population (n=634)

Tiredness was found to be the most reported symptoms, with 77.0% (n=891) of the respondents reported experiencing it. Besides that, symptoms such as trouble sleeping (n=769, 66.5%) and headaches (n=684, 59.1%) are experienced by more than half of the respondents. Other psychosomatic symptoms such as dizziness (n=538, 46.5%) and pain in arms, legs or joint (n=493, 42.6%) were also found to be among the top 5 reported symptoms. On a side note, menstrual cramps or period problem which occurs only among the female population were also found to occur quite frequently with 45.4% (n=288) of the females reported experiencing it. Meanwhile, other symptoms as shown in Table 4.29 were found to have less impact on the psychosomatic health of the urban communities in the study area. Further analysis was conducted to identify the prevalence of psychosomatic health symptoms according to selected sociodemographic indicators. The findings are presented in the following sub-section.

4.4.2.1 Patient Health Questionnaire-15 health impact score

Patient health questionnaire 15 (PHQ-15) is a validated screening tool to screen for the severity of psychosomatic symptoms among the urban communities in the study area. In this study, the psychosomatic symptom scores were clustered into low severity and high severity. The severity of psychosomatic symptoms according to the PHQ-15 scores among the urban community in the study area is summarized in Table 4.29.

Table 4.29: Mean and standard deviation of PHQ-15 scores

Variables	Participants (n = 1052)	PHQ-15 Score	95% CI	
	n (%)	Mean ± SD	Lower	Upper
Psychosomatic Symptom Severity				
High (10 - 30)	359 (34.1)	14.62 ± 4.21	14.18	15.06
Low (0 - 9)	693 (65.9)	4.81 ± 2.84	4.60	5.02

The prevalence of high severity of psychosomatic symptoms among the urban community was found to be 34.1% (n=359) with a mean score of 14.62 (SD=4.21). Meanwhile, 65.9% (n=693) of the respondents had low severity with a mean score of 4.81 (SD=2.84). In the following analysis, the sociodemographic factors influencing the severity of psychosomatic symptoms were identified.

4.4.2.2 Factors influencing severity of psychosomatic symptoms

The information gathered through the sociodemographic of the respondents is associated with the psychosomatic symptoms. In general, urban communities that were found to have high severity of psychosomatic symptoms in this study are female (n=214, 20.3%), less than 20 years old (n=139, 13.3%), Malay (n=194, 18.9%), spend 3 to 5 hour a day at outdoors (n=116, 11.4%) and reported neutral or negative thermal response (n=176, 22.3%). Through univariate binary logistic regression analysis, it was identified that age group and ethnicity were confounders for the severity of psychosomatic symptoms. Interestingly, PET was not significantly associated with the severity of psychosomatic symptoms indicating the minimal influence of OTC level on psychosomatic outcomes.

In continuation, multivariate logistic regression was performed to adjust for confounding variables to PET and psychosomatic symptoms. To avoid the risk of missing important variables, variables in the univariate model such as duration spent outdoors in a day ($p=0.090$) and PET ($p=0.113$) that have shown a relaxed p-value ($p \leqslant 0.25$) were also included in the multivariate model (Sperandei, 2014). Table 4.30 summarizes the interaction between the sociodemographic factors and PET level with the severity level of psychosomatic symptoms.

Table 4.30: Univariate and multivariate analysis of psychosomatic symptoms according to sociodemographic

Variables	Participants	Psychosomatic symptom severity		Univariate analysis[1]		Multivariate analysis[2]	
		High (10 - 30)	Low (0 - 9)	cOR (95% CI)	p-value	aOR (95% CI)	p-value
	n (%)	n (%)	n (%)				
Gender (n = 1052)							
Male	447 (42.5)	145 (13.8)	302 (28.7)	0.88 (0.68, 1.14)	**0.321**	-	**-**
Female	605 (57.5)	214 (20.3)	391 (37.2)	Reference	**-**	Reference	**-**
Age group (n = 1042)					**0.009***		**0.002***
< 20 years	338 (32.4)	139 (13.3)	199 (19.1)	1.66 (1.16, 2.37)	**0.006***	2.38 (1.50, 3.80)	**<0.001***
20 -23 years	214 (20.5)	64 (6.1)	150 (14.4)	1.01 (0.67, 1.52)	**0.952**	1.28 (0.77, 2.12)	**0.339**
24 - 31 years	264 (25.3)	84 (8.1)	180 (17.3)	1.11 (0.75, 1.63)	**0.604**	1.32 (0.83, 2.08)	**0.237**
> 31 years	226 (21.7)	67 (6.4)	159 (15.3)	Reference	**-**	Reference	**-**
Ethnicity (n = 1029)					**<0.001***		**<0.001***
Malay	468 (45.5)	194 (18.9)	274 (26.6)	1.54 (0.96, 2.48)	**0.077**	1.68 (0.83, 3.37)	**0.149**
Chinese	404 (39.3)	104 (10.1)	300 (29.2)	0.75 (0.46, 1.23)	**0.260**	0.65 (0.31, 1.34)	**0.239**
Indian	65 (6.3)	24 (2.3)	41 (4.0)	1.27 (0.65, 2.48)	**0.481**	1.31 (0.54, 3.16)	**0.555**
Others	92 (8.9)	29 (2.8)	63 (6.1)	Reference	**-**	Reference	**-**

Table 4.30: Univariate and multivariate analysis of psychosomatic symptoms according to sociodemographic (continued)

Variables	Participants	Psychosomatic symptom severity		Univariate analysis[1]		Multivariate analysis[2]	
		High (10 - 30)	Low (0 - 9)	cOR (95% CI)	p-value	aOR (95% CI)	p-value
	n (%)	n (%)	n (%)				
Duration spent outdoors in a day (n = 1018)					**0.090**		**0.224**
< 3 hours	220 (21.6)	60 (5.9)	160 (15.7)	0.62 (0.42, 0.91)	**0.016**	0.65 (0.41, 1.04)	**0.071**
3 - 5 hours	326 (32.0)	116 (11.4)	210 (20.6	0.91 (0.64, 1.28)	**0.577**	0.97 (0.64, 1.47)	**0.872**
5 - 9 hours	229 (22.5)	81 (8.0)	148 (14.5)	0.90 (0.62, 1.31)	**0.575**	0.95 (0.60, 1.49)	**0.817**
> 9 hours	243 (23.9)	92 (9.0)	151 (14.8)	Reference	**-**	Reference	**-**
Physiological Equivalent Temperature (n = 788)							
Positive Thermal Response	493 (62.6)	122 (15.5)	173 (22.0)	1.27 (0.95, 1.71)	**0.113**	1.10 (0.80, 1.51)	**0.546**
Neutral and Negative Thermal Response	295 (37.4)	176 (22.3)	317 (40.2)	Reference	**-**	Reference	**-**

[1]Unadjusted model

[2]Model adjusted for age group, ethnicity, duration spent outdoors in a day, PET

In the multivariate model, the same significant association was found with new adjusted Odd Ratios (aOR) considering age group, ethnicity, duration spent outdoors in a day and PET. According to the aOR, urban communities that reported positive thermal response are 1.1 times higher odds of having moderate to high severity of psychosomatic symptoms as compared to those that reported neutral and negative thermal response (OR=1.10, 95% CI: 0.80-1.51). However, as PET was not significantly correlated with the severity of psychosomatic symptoms (even after the adjustment with confounding factors), the OTC level is believed to have minimal influence on the severity of psychosomatic symptoms.

Through literature review, gender was found to be a critical determinant of expressing psychosomatic symptoms (Beutel et al., 2019; Hinz et al., 2017). However, through this study, it was found that the association of gender were not significantly affecting the outcome of psychosomatic symptoms. This contradicts with the findings of Bartley and Fillingnim (2013) which reported intense psychosomatic severity among women as compared to men because of the differences in brain function, hormones, and reproductive processes (Bartley & Fillingim, 2013; Nakao et al., 2001).

The duration spent outdoors in a day ($p>0.05$) was also insignificantly affecting the outcome of psychosomatic symptoms. Logically speaking, the longer exposure in the outdoor environment would have a linear relationship with the health outcome. This finding reassures the effect of duration of exposure in a day towards the stable OTC level throughout a day as shown in Section 4.3.5.

In terms of age group, respondents who are less than 20 years old had the highest prevalence of moderate-to-high psychosomatic symptoms (n=139, 13.3%) as compared to the other groups. Those who are in this group are about 2.4 times (OR=2.38, 95% CI: 1.50, 3.80) more likely to report psychosomatic symptoms as compared to those that are more than 31 years old. This finding contradicts with the findings from Hinz et al. (2017) where older respondents were found to be more associated with psychosomatic symptoms. One of the possible reasons for this contradiction could be due to the reclassified age range to ensure an equally distributed age group for data analysis in this study (Hinz et al., 2017). As the current study was an attempt to understand the impact of urban heat on health outcomes affecting the general people, the limitations in the cross-sectional approach could be further explored through future studies.

Ethnicity was also found to be a significant confounder influencing the prevalence of psychosomatic symptoms. Malay (n=194, 18.9%) was found to report the highest severity of psychosomatic symptoms as compared to Chinese (n=104, 10.1%), Indian (n=24, 2.3%), and other ethnicities (n=29, 2.8%). Further elaboration on the prevalence of psychosomatic symptoms is presented in the following sub-section.

4.4.2.3 Components of psychosomatic health symptoms

Through EFA, all the items in PHQ-15 representing psychosomatic symptoms are loaded into three components which were then classified as symptoms related to cardiopulmonary, pain and fatigue. Table 4.31 summarizes the psychosomatic symptoms according to each component.

Table 4.31: Psychosomatic symptoms according to the components generated through Exploratory Factor Analysis

Components	Cardiopulmonary	Pain	Fatigue
Symptoms	Fainting spells	Back pain	Feeling tired or having little energy
	Dizziness	Pain in arms, legs, or joints of knees, hips, etc.	
	Feeling heart pound or race	Stomach pain	Trouble falling or staying asleep
	Chest pain	Nausea, gas, or indigestion	
	Headache	Constipation or diarrhoea	
	Shortness of breath		

The associations of PET with each component of the psychosomatic symptoms were performed to identify the influence of sociodemographic indicators as confounding factors. PET was significantly associated with pain symptoms while symptoms related to cardiopulmonary and fatigue were not significantly associated. The associations of psychosomatic health components with PET according to the sociodemographic are summarized in Table 4.32.

Table 4.32: Psychosomatic health components according to sociodemographic

Variables	Participants	Psychosomatic symptoms		
		Cardiopulmonary (6 items)	Pain (5 items)	Fatigue (2 items)
	n (%)	Median (IQR)		
Gender (n = 1052)				
Male	447 (42.5)	2.00 (3.00)	2.00 (4.00)	2.00 (2.00)
Female	605 (57.5)	2.00 (4.00)	2.00 (3.00)	2.00 (2.00)
p value		**0.036***	**0.900**	**<0.001***
Age group (n = 1042)				
< 20 years	338 (32.4)	3.00 (4.00)	2.00 (4.00)	2.00 (2.00)
20 - 23 years	214 (20.5)	2.00 (3.00)	2.00 (3.00)	2.00 (1.00)
24 - 31 years	264 (25.3)	2.00 (3.00)	1.00 (3.75)	2.00 (2.00)
> 31 years	226 (21.7)	2.00 (4.00)	2.00 (4.00)	2.00 (2.00)
p value		**0.009***	**0.644**	**<0.001***
Ethnicity (n = 1029)				
Malay	468 (45.5)	3.00 (4.00)	2.00 (3.75)	2.00 (2.00)
Chinese	404 (39.3)	2.00 (4.00)	0.50 (2.00)	2.00 (2.00)
Indian	65 (6.3)	2.00 (3.25)	2.00 (3.25)	2.00 (2.25)
Others	92 (8.9)	2.00 (4.00)	2.00 (3.75)	2.00 (2.00)
p value		**0.002***	**<0.001***	**0.085**

Table 4.32: Psychosomatic health components according to sociodemographic (continued)

Variables	Participants	Psychosomatic symptoms		
		Cardiopulmonary (6 items)	Pain (5 items)	Fatigue (2 items)
	n (%)	Median (IQR)		
Duration spent outdoors in a day (n = 1018)				
< 3 hours	220 (21.6)	2.00 (3.00)	1.00 (3.00)	2.00 (2.00)
3 - 5 hours	326 (32.0)	2.00 (3.25)	2.00 (3.00)	2.00 (2.00)
5 - 9 hours	229 (22.5)	2.00 (3.00)	2.00 (3.00)	2.00 (2.00)
> 9 hours	243 (23.9)	3.00 (4.00)	2.00 (4.00)	2.00 (2.00)
p value		**0.046***	**<0.001***	**0.013***
Physiological Equivalent Temperature (n = 788)				
Positive Thermal Response	493 (62.6)	3.00 (4.00)	2.00 (4.00)	2.00 (2.00)
Neutral and Negative Thermal Response	295 (37.4)	2.00 (3.00)	2.00 (4.00)	2.00 (2.00)
p value		**0.307**	**0.016***	**0.577**

According to Table 4.32, PET level was found to be significantly associated with pain symptoms. When exposed to high ambient temperatures, people can experience heat exhaustion or heat cramps as a result of body-overheating with several symptoms such as pain in a limb or joint areas as well as feeling nauseous (Centers of Disease Control and Prevention, 2017). Besides that, other symptoms such as stomach or abdominal pain and constipation are precursors to heat cramps and dehydration (Popkin et al., 2010), respectively.

On the contrary, PET level was found to be not significantly associated with cardiopulmonary and fatigue symptoms in this study, although there are reasons to believe otherwise. The three health components of psychosomatic symptoms are closely associated with the human thermoregulation system which is expected to aggravate in the presence of heat stress. When exposed to a hot environment, the cutaneous thermo-receptors would liaise with the thermoregulatory centre to initiate a mechanism to offset the temperature gradient between the integument and body core (Li et al., 2017). The heat exchange between the body and the surrounding environment is controlled through vasodilation and sweating which is fundamental to facilitate heat dissipation (Li et al., 2017). As these thermoregulatory changes require abundant energy consumption, it is expected for the people to experience fatigue, headaches and dizziness in a hot environment. One of the possible reasons for the insignificant association could lie in the way the respondents perceived the thermal environment as expressed through PET. As indicated in the earlier sections, the respondents in the study area exhibit thermal acclimatization. Hence, the model generated here to describe the association of PET with psychosomatic symptoms may be affected by the adaptive behaviour as well.

Gender was found to be a critical determinant of expressing psychosomatic symptoms but it was found through this study that the association of gender were only affecting cardiopulmonary (p=0.036) and fatigue (p<0.001) related psychosomatic symptoms while pain (p=0.900) symptoms were not found to be significantly affected. This finding could be interconnected with the duration of exposure in a day according to the genders as shown in Table 4.17. The longer hours spent outdoors by males could trigger higher prevalence of cardiopulmonary and fatigue-related symptoms.

Similarly, the influence of the age group as a confounding factor was significant for cardiopulmonary (p=0.009) and fatigue (p<0.001) symptoms. However, those that are less than 20 years old are found to report a higher median score of 3 [IQR=4] as compared to the other age groups which are reporting a median score of 2 for cardiopulmonary related symptoms. This finding is unusual because cardiopulmonary related complications are known to be more prevailing as a person gets older (Hinz et al., 2017; Kenney et al., 2014). On the other hand, the median score 2 was reported for all age group under fatigue symptoms. This indicates that the urban communities in the study area express fatigue-related symptoms in the same manner across the different age groups.

The influence of ethnicity as a confounding factor significantly affected cardiopulmonary and pain-related symptoms. From the analysis, it was found that Chinese reported significantly lower cardiopulmonary symptoms (median score=2 [IQR=4]) as compared to Malay (median score=3 [IQR=4]). Similarly, the same trend was found in pain-related symptoms. This finding could be related to the duration spent outdoors according to ethnic as shown in Table 4.17. The duration of exposure in a day at outdoor environment due to nature of work influenced not only the physical health but also towards the psychosomatic and psychological health of the urban communities in the study area.

The adverse pain due to body-heating was found to be significantly associated with thermal discomfort (Näyhä et al., 2014). Hence, the longer duration of outdoor exposure is postulated to influence the health outcome as the daytime outdoor thermal environment is very uncomfortable especially between 11.00 am to 4.00 pm (Johansson et al., 2013; Ndetto & Matzarakis, 2013; Yahia & Johansson, 2013). Through multivariate analysis, the duration spent outdoors in a day is found to be significantly associated with cardiopulmonary, pain and fatigue symptoms. It was revealed that those who spent more than 9 hours in a day at outdoors had significantly higher cardiopulmonary symptoms (median score=3 [IQR=4]) compared to those who spent lesser than 9 hours in a day at outdoor areas. The difference in duration of outdoor exposure as shown in Table 4.17 could be the explanation for the variations in psychosomatic health outcome such as why the Chinese were found to report lower pain symptoms (median score=0.5 [IQR=2]) as compared to the Malays (median score=2, [IQR=3.75]).

Besides the long hour of urban heat exposure in a day, the urban heat exposure in the hottest period also has considerable impact on a person's health and well-being. According to the American Heart Association (2015), the general population staying at outdoors from 12.00 pm to about 3.00 pm is prone to heart-related problems especially among the elderly diagnosed with heart diseases (American Heart Association, 2015). Findings from other studies also suggested the influence of higher temperature inducing physiological changes such as heart rate, blood pressure, blood cholesterol level, inflammatory reaction and immune function which may affect a person's cardiovascular system (Feigin et al., 2016; Halonen et al., 2011; Keatinge et al., 1984; Keatinge et al., 1986). However, such findings would require a longitudinal approach as opposed to the cross-sectional approach in the current study. Future studies on the influence of the thermal environment in a tropical climate on the psychosomatic health outcome should consider the long-term impact of urban heat as well. Meanwhile, the prevalence of psychological symptoms as related to urban heat exposure is presented in the next section.

4.4.3 Prevalence of psychological symptoms from heat exposure

The psychological symptoms were further separated according to anxiety and depression symptoms. Commonly reported anxiety-related psychological symptoms from heat exposure is summarized in Table 4.33.

Table 4.33: Summary of reported anxiety-related psychological symptoms from heat exposure

Rank according to most reported symptoms	Symptoms	Frequency (%) (n=1160)
Anxiety		
1	Feeling nervous or anxious	518 (44.7)
2	Trouble relaxing	509 (43.9)
3	Easily annoyed or irritable	471 (40.6)
4	Worrying too much about different things	439 (37.8)
5	Not able to stop or control worrying	437 (37.7)
6	Restless	407 (35.1)
7	Feeling afraid of something awful happening	187 (16.1)

In terms of anxiety-related psychological health symptoms, about 35% to 45% of the respondents reported that they are having issues with feeling nervous (n=518, 44.7%), trouble relaxing (n=509, 43.9%), easily annoyed (n=471, 40.6%), worrying too much (n=439, 37.8%), not able to control worrying (n=437, 37.7%) and being restless (n=407, 35.1%). Meanwhile, commonly reported depression-related psychological symptoms from heat exposure is summarized in Table 4.34.

Table 4.34: Summary of reported depression related psychological symptoms from heat exposure

Rank according to most reported symptoms	Symptoms	Frequency (%) (n=1160)
Depression		
1	Feeling tired or having little energy	872 (75.2)
2	Little interest or pleasure in doing things	717 (61.8)
3	Poor appetite or overeating	715 (61.6)
4	Trouble falling or staying asleep	708 (61.0)
5	Trouble concentrating at home, school, work or while doing other things?	674 (58.1)
6	Feeling down, depressed or hopeless	636 (54.8)
7	Having thoughts that you would be better off dead or hurting yourself in some way	550 (47.4)
8	Feeling bad about yourself	527 (45.4)
9	Unusual moving or speaking speed	465 (40.1)

Commonly reported depression-related psychological health symptoms are feeling tired (n=872, 75.2%), little interest in doing things (n=717, 61.8%), poor appetite or overeating (n=715, 61.6%), trouble falling or staying asleep (n=708, 61.0%) and trouble with concentrating at home, school, work or while doing other things (n=674, 58.1%). Shockingly, there are a considerable number of respondents (n=550, 47.4%) having suicidal thoughts and the tendency to self-harm. Meanwhile, other symptoms shown in Table 4.34 were found to have less impact on the psychological health of the urban communities in the study area.

Besides the occurrence of the psychological symptoms, the respondents were also asked regarding the frequency of experiencing particular symptoms as a result of urban heat exposure. The rate of recurrence of psychological symptoms is summarized in Table

4.35. On a nearly everyday basis, respondents has issues with feeling tired or having little energy (n=115, 9.9%), trouble concentrating at home, school, work or while doing other things (n=100, 8.6%), trouble falling or staying asleep (n=93, 8.0%), easily annoyed or irritable (n=74, 6.4%) and worrying too much about different things (n=56, 4.8%). Occasionally, on the scale of several days to more than a week, respondents were also found to have little interest or pleasure in doing things (n=116, 10.0%). Further analysis was conducted to identify the prevalence of anxiety-related psychological health symptoms and depression-related psychological health symptoms according to selected sociodemographic indicators. The findings are presented in the following sub-sections.

Table 4.35: The rate of recurrence of psychological symptoms from heat exposure

Rank	Symptoms	Frequency (%) (n=1160)		
		Nearly every day	More than a week	Several days
1	Feeling tired or having little energy	115 (9.9)	214 (18.4)	543 (46.8)
2	Trouble concentrating at home, school, work or while doing other things?	100 (8.6)	197 (17.0)	418 (36.0)
3	Trouble falling or staying asleep	93 (8.0)	165 (14.2)	450 (38.8)
4	Easily annoyed or irritable	74 (6.4)	161 (13.9)	439 (37.8)
5	Worrying too much about different things	56 (4.8)	124 (10.7)	338 (29.1)
6	Trouble relaxing	55 (4.7)	150 (12.9)	431 (37.2)
7	Little interest or pleasure in doing things	51 (4.4)	116 (10.0)	550 (47.4)
8	Feeling bad about yourself	48 (4.1)	121 (10.4)	270 (23.3)
9	Restless	41 (3.5)	129 (11.1)	339 (29.2)
10	Poor appetite or overeating	39 (3.4)	151 (13.0)	360 (31.0)
11	Feeling afraid of something awful happening	39 (3.4)	79 (6.8)	319 (27.5)
12	Not able to stop or control worrying	35 (3.0)	95 (8.2)	341 (29.4)
13	Feeling down, depressed or hopeless	33 (2.8)	118 (10.2)	376 (32.4)
14	Feeling nervous or anxious	24 (2.1)	59 (5.1)	382 (32.9)
15	Unusual moving or speaking speed	22 (1.9)	81 (7.0)	304 (26.2)
16	Having thoughts that you would be better off dead or hurting yourself in some way	18 (1.6)	33 (2.8)	136 (11.7)

4.4.3.1 Anxiety health impact score

The anxiety health impact score which is based on GAD-7 score is a validated screening tool to screen for anxiety severity among the urban communities in the study area. In this study, the anxiety health impact scores were clustered into low severity and high severity. The prevalence of high anxiety severity among the urban community was found to be 15.4% (n=169) with a mean score of 12.51 (SD=2.59) while 84.6% (n=931) of the respondents had low severity with a mean score of 3.25 (SD=2.91). Table 4.36 summarized the severity of anxiety scores by the respondents.

Table 4.36: Mean and standard deviation of anxiety score

Variables	Participants (n = 1100)	GAD-7 Score	95% CI	
	n (%)	Mean ± SD	Lower	Upper
Anxiety Severity				
High (10 - 21)	169 (15.4)	12.51 ± 2.59	12.12	12.90
Low (0 - 9)	931 (84.6)	3.25 ± 2.91	3.07	3.44

In the subsequent analysis, sociodemographic factors which influenced the severity of anxiety symptoms were identified. In general, urban communities that were found to have high severity of anxiety symptoms are female (n=109, 9.8%), less than 20 years old (n=71, 6.5%), Malay (n=80, 7.4%), spend 3 to 5 hour a day at outdoors (n=61, 5.7%) and reported neutral or negative thermal response (n=73, 9.0%). Through univariate binary logistic regression analysis, it was identified that gender and age group were confounders for the severity of anxiety symptoms.

In continuation, multivariate logistic regression was performed to adjust for confounding variables to PET and anxiety symptoms. Variables in the univariate model that have shown a relaxed p-value ($p \leqslant 0.25$) such as duration spent outdoors in a day ($p=0.138$) and PET ($p=0.060$) were also included in the multivariate model. Table 4.37 summarizes the interaction between the sociodemographic factors and PET level with the severity level of anxiety symptoms.

In the multivariate model, the PET was found to be significantly associated with the severity of anxiety symptoms by controlling for gender. The adjusted odds ratio (aOR) revealed that urban communities that reported positive thermal response are 1.6 times higher odds of having high severity of anxiety symptoms than those that reported neutral and negative thermal response (OR=1.58, 95% CI: 1.07-2.32). This finding provided evidence that there is a considerable influence of OTC level at urban outdoors towards the outcome of anxiety symptoms by controlling for gender as a confounding factor.

Unlike other physical and psychosomatic related health symptoms, all anxiety-related psychological symptoms were loaded into a single component through EFA. Therefore, Mann Whitney U or Kruskal Wallis H test did not proceed for the anxiety health impact score.

Table 4.37: Univariate and multivariate analysis for anxiety severity according to sociodemographic

Variables	Participants	Anxiety severity		Univariate analysis[1]		Multivariate analysis[2]	
		High (10 - 21)	Low (0 - 9)	cOR (95% CI)	p-value	aOR (95% CI)	p-value
	n (%)	n (%)	n (%)				
Gender (n = 1100)							
Male	490 (44.5)	61 (5.5)	429 (39.0)	0.66 (0.47, 0.93)	**0.017***	0.59 (0.40, 0.88)	**0.010***
Female	610 (55.5)	108 (9.8)	502 (45.6)	Reference	-	Reference	-
Age group (n = 1089)					**0.037***		**0.161**
< 20 years	354 (32.5)	71 (6.5)	283 (26.0)	1.56 (1.00, 2.42)	**0.050**	1.26 (0.76, 2.08)	**0.373**
20 -23 years	216 (19.8)	26 (2.4)	190 (17.4)	0.85 (0.49, 1.46)	**0.553**	0.73 (0.37, 1.41)	**0.344**
24 - 31 years	267 (24.5)	37 (3.4)	230 (21.1)	1.00 (0.61, 1.64)	**0.992**	0.75 (0.41, 1.38)	**0.355**
> 31 years	252 (23.1)	35 (3.2)	217 (19.9)	Reference		Reference	-
Ethnicity (n = 1074)					**0.716**		-
Malay	488 (45.4)	80 (7.4)	408 (38.0)	1.05 (0.57, 1.91)	**0.884**	-	-
Chinese	418 (38.9)	57 (5.3)	361 (33.6)	0.84 (0.45, 1.56)	**0.586**	-	-
Indian	73 (6.8)	11 (1.0)	62 (5.8)	0.95 (0.41, 2.20)	**0.898**	-	-
Others	95 (8.8)	15 (1.4)	80 (7.4)	Reference	-	Reference	-

Table 4.37: Univariate and multivariate analysis for depression severity according to sociodemographic (continued)

Variables	Participants	Anxiety severity		Univariate analysis[1]		Multivariate analysis[2]	
		High (10 - 21)	Low (0 - 9)	cOR (95% CI)	p-value	aOR (95% CI)	p-value
	n (%)	n (%)	n (%)				
Duration spent outdoors in a day (n = 1064)					**0.138**		**0.094**
< 3 hours	231 (21.7)	25 (2.3)	206 (19.4)	0.64 (0.38, 1.09)	**0.102**	0.72 (0.38, 1.35)	**0.302**
3 - 5 hours	338 (31.8)	61 (5.7)	277 (26.0)	1.16 (0.75, 1.80)	**0.502**	1.44 (0.85, 2.44)	**0.177**
5 - 9 hours	244 (22.9)	39 (3.7)	205 (19.3)	1.00 (0.62, 1.62)	**0.989**	1.10 (0.62, 1.96)	**0.747**
> 9 hours	251 (23.6)	40 (3.8)	211 (19.8)	Reference	**-**	Reference	**-**
Physiological Equivalent Temperature (n = 815)							
Positive Thermal Response	305 (37.4)	59 (7.2)	246 (30.2)	1.44 (0.99, 2.09)	**0.060**	1.58 (1.07, 2.32)	**0.022***
Neutral and Negative Thermal Response	510 (62.6)	73 (9.0)	437 (53.6)	Reference	**-**	Reference	**-**

[1]Unadjusted model

[2]Model adjusted for gender, age group, duration spent outdoors in a day, PET

4.4.3.2 Depression health impact score

The patient health questionnaire 9 (PHQ-9) is a validated screening tool used to screen for the severity of depression (Kroenke & Spitzer, 2002) among the urban communities in the study area. In this study, the depression severity scores were clustered into 0 to 9 for low severity and 10 to 27 for high severity. The mean and standard deviation of the depression severity score for the urban community is shown in Table 4.38.

Table 4.38: Mean and standard deviation of depression score

Variables	Participants (n = 1095)	PHQ-9 Score	95% CI	
	n (%)	Mean ± SD	Lower	Upper
Depression Severity				
High (10 - 27)	296 (27.0)	13.68 ± 3.08	13.32	14.03
Low (0 - 9)	799 (73.0)	4.11 ± 2.85	3.91	4.31

The prevalence of high depression severity among the urban community was found to be 27.0% (n=296) with a mean score of 13.68 (SD=3.08). Meanwhile, 73.0% (n=799) of the respondents had low depression severity with a mean score of 4.81 (SD=2.84). In the subsequent analysis, the sociodemographic factors influencing the severity of depression symptoms were identified. In general, urban communities that were found to have high severity of depression symptoms are female (n=172, 15.7%), less than 20 years old (n=119, 11.0%), Malay (n=153, 14.3%), spend 3 to 5 hour a day at outdoors (n=105, 9.9%) and reported neutral or negative thermal response (n=152, 18.8%).

Through univariate binary logistic regression analysis, it was identified that the age group and ethnicity were confounders for the severity of depression symptoms. In continuation, multivariate logistic regression was performed to adjust for confounding variables relative to PET and depression symptoms. Variables in the univariate model such as duration spent outdoors in a day ($p=0.175$) and PET ($p=0.130$) that have shown a relaxed p-value ($p \leqslant 0.25$) were also included in the multivariate model. Table 4.39 summarizes the interaction between the sociodemographic factors and PET level with the severity level of depression symptoms.

In the multivariate model, the same significant association was found with the new adjusted Odd Ratios (aOR) considering age group, ethnicity, duration spent outdoors in a day and PET. According to the aOR, urban communities that reported positive thermal response are 1.2 times or 20% higher odds of having high severity of depression symptoms as compared to those that reported neutral or negative thermal response (OR=1.17, 95% CI: 0.85-1.61). However, as PET was not found to be statistically significant with the severity of depression symptoms, the OTC level is said to have minimal influence on the severity of depression outcomes. In further analysis, EFA is conducted to identify if there are clusters of depression symptoms associated with sociodemographic and PET level which is presented in the subsequent section.

Table 4.39: Univariate and multivariate analysis for depression severity according to sociodemographic

Variables	Participants	Depression severity		Univariate analysis[1]		Multivariate analysis[2]	
		High (10 - 27)	Low (0 - 9)	cOR (95% CI)	p-value	aOR (95% CI)	p-value
	n (%)	n (%)	n (%)				
Gender (n = 1095)							
Male	489 (44.7)	124 (11.3)	365 (33.3)	0.86 (0.66, 1.12)	**0.263**	-	**-**
Female	606 (55.3)	172 (15.7)	434 (39.4)	Reference		Reference	**-**
Age group (n = 1085)					**0.006***		**0.022***
< 20 years	350 (32.3)	119 (11.0)	231 (21.3)	1.80 (1.25, 2.61)	**0.002***	2.05 (1.29, 3.26)	**0.003***
20 -23 years	215 (19.8)	55 (5.1)	160 (14.7)	1.20 (0.79, 1.84)	**0.396**	1.56 (0.94, 2.59)	**0.085**
24 - 31 years	268 (24.7)	66 (6.1)	202 (18.6)	1.14 (0.76, 1.72)	**0.518**	1.26 (0.79, 2.01)	**0.341**
> 31 years	252 (23.2)	56 (5.2)	196 (18.1)	Reference	**-**	Reference	**-**
Ethnicity (n = 1071)					**0.013***		**0.013***
Malay	484 (45.2)	153 (14.3)	331 (30.9)	2.12 (1.21, 3.71)	**0.008***	2.52 (1.12, 5.69)	**0.026***
Chinese	417 (38.9)	102 (9.5)	315 (29.4)	1.49 (0.84, 2.63)	**0.174**	1.48 (0.64, 3.40)	**0.361**
Indian	75 (7.0)	18 (1.7)	57 (5.3)	1.45 (0.69, 3.05)	**0.330**	1.55 (0.58, 4.14)	**0.383**
Others	95 (8.9)	17 (1.6)	78 (7.3)	Reference	**-**	Reference	**-**

Table 4.39: Univariate and multivariate analysis for depression severity according to sociodemographic (continued)

Variables	Participants n (%)	Depression Severity High (10 - 27) n (%)	Depression Severity Low (0 - 9) n (%)	Univariate analysis[1] cOR (95% CI)	Univariate analysis[1] p-value	Multivariate analysis[2] aOR (95% CI)	Multivariate analysis[2] p-value
Duration spent outdoors in a day (n = 1061)					**0.175**		**0.086**
< 3 hours	228 (21.5)	54 (5.1)	174 (16.4)	0.95 (0.62, 1.44)	**0.795**	1.06 (0.65, 1.72)	**0.820**
3 - 5 hours	337 (31.8)	105 (9.9)	232 (21.9)	1.38 (0.96, 1.99)	**0.087**	1.63 (1.06, 2.51)	**0.027***
5 - 9 hours	245 (23.1)	69 (6.5)	176 (16.6)	1.20 (0.80, 1.78)	**0.382**	1.23 (0.77, 1.96)	**0.397**
> 9 hours	251 (23.7)	62 (5.8)	189 (17.8)	Reference	**-**	Reference	**-**
Physiological Equivalent Temperature (n = 809)							
Positive Thermal Response	300 (37.1)	105 (13.0)	195 (24.1)	1.27 (0.93, 1.71)	**0.130**	1.17 (0.85, 1.61)	**0.338**
Neutral and Negative Thermal Response	509 (62.9)	152 (18.8)	357 (44.1)	Reference	**-**	Reference	**-**

[1]Unadjusted model

[2]Model adjusted for age group, ethnicity, duration spent outdoors in a day, PET

4.4.3.3 Health components within depressive symptoms

Through EFA, depression-related psychological symptoms are clustered into two components which were then classified as symptoms related to somatization and depression. Table 4.40 summarizes the depression symptoms according to each component.

Table 4.40: Depression-related psychological symptoms according to the components generated through Exploratory Factor Analysis

Components	Somatization	Depression
Symptoms	Feeling tired or having little energy	Feeling down, depressed or hopeless
	Little interest or pleasure in doing things	Having negative thoughts
	Trouble falling or staying asleep	Unusual moving or speaking speed
	Poor appetite or overeating	Feeling bad about oneself
	Trouble concentrating at home, school, work or while doing other things	

The association of depressive health components with PET according to the sociodemographic is summarized in Table 4.41.

Table 4.41: Depressive components according to sociodemographic variables

Variables	Participants	Depressive components	
		Somatization (5 items)	Depression (4 items)
	n (%)	Median score (IQR)	
Gender (n = 1095)			
Male	489 (44.7)	5.00 (6.00)	1.00 (2.00)
Female	606 (55.3)	5.00 (5.00)	1.00 (2.00)
p value		**0.015***	**0.717**
Age group (n = 1085)			
< 20 years	350 (32.3)	6.00 (6.00)	1.00 (3.00)
20 -23 years	215 (19.8)	4.00 (5.00)	1.00 (2.00)
24 - 31 years	267 (24.7)	5.00 (5.00)	0.00 (2.00)
> 31 years	249 (23.2)	4.00 (6.50)	0.00 (2.00)
p value		**<0.001***	**<0.001***
Ethnicity (n = 1071)			
Malay	484 (45.2)	5.00 (6.00)	1.00 (3.00)
Chinese	415 (38.9)	4.00 (5.00)	1.00 (2.00)
Indian	73 (7.0)	4.00 (6.00)	0.00 (2.00)
Others	95 (8.9)	4.00 (5.00)	0.00 (1.00)
p value		**<0.001***	**<0.001***
Duration spent outdoors in a day (n = 1061)			
< 3 hours	228 (21.5)	4.00 (6.00)	0.00 (1.75)
3 - 5 hours	335 (31.8)	5.00 (6.00)	1.00 (2.00)
5 - 9 hours	243 (23.1)	5.00 (5.00)	1.00 (2.00)
> 9 hours	251 (23.7)	5.00 (4.00)	1.00 (3.00)
p value		**0.070**	**<0.001***
Physiological Equivalent Temperature (n = 809)			
Positive Thermal Response	300 (37.1)	6.00 (6.00)	1.00 (3.00)
Neutral and Negative Thermal Response	505 (62.9)	5.00 (5.50)	1.00 (2.00)
p value		**0.041***	**0.092**

PET was found to be significantly related with somatization symptoms such as feeling tired or having little energy, little interest or pleasure in doing things, trouble falling or staying asleep, poor appetite or overeating, and trouble concentrating at home, school, work or while doing other things. This association is logical because an individual under thermal stress in a hot environment is prone to experience dizziness, energy depletion and central fatigue (Centers of Disease Control and Prevention, 2017). Besides, people often felt lethargic in a hot environment because more energy is required for homeostasis to regulate internal temperature (McKinley et al., 2018; Sawka et al., 2013). Findings from Okamoto-Mizuno and Mizuno (2011) also confirmed the presence of heat disturbing an individual's sleeping pattern (Okamoto-Mizuno & Mizuno, 2011). From another study, the hot-humid exposure which increases the thermal load during sleep was found to affect sleep stages and causes tiredness (Okamoto-Mizuno & Mizuno, 2012).

On the other hand, PET was found to be not significant with depressive symptoms such as feeling down, depressed or hopeless, having negative thoughts, unusual moving or speaking speed, and feeling bad about oneself. One of the possible explanations could be related to the level of severity of the aforementioned symptoms. The urban community may find the depressive symptoms to be very severe and do not presume the direct causal influence of the thermal environment towards the outcome of these depressive symptoms.

In short, the OTC level was found to significantly induced somatization related symptoms while not causing depressive symptoms among the urban community. However, the rather high numbers of respondents (n=550, 47.4%) reported having suicidal thoughts and the tendency to self-harm indicates that considerable attention has to be given towards promoting good mental health among the urban communities. Although the short-term impacts (a daily occurrence) of urban heat on psychological health outcomes were found to affect a small fraction of urban communities in the current study, the long-term impacts may have very different outcomes which deserve future studies. Nevertheless, this study succeeded to unravel some of the association between urban heat exposure towards the outcome of psychological health.

4.4.4 Outdoor thermal discomfort as a public health issue

In the last section of the questionnaire, the respondents were asked if the outdoor thermal discomfort should be considered as a public health issue. The respondent's opinion is summarized in Figure 4.20 as shown below.

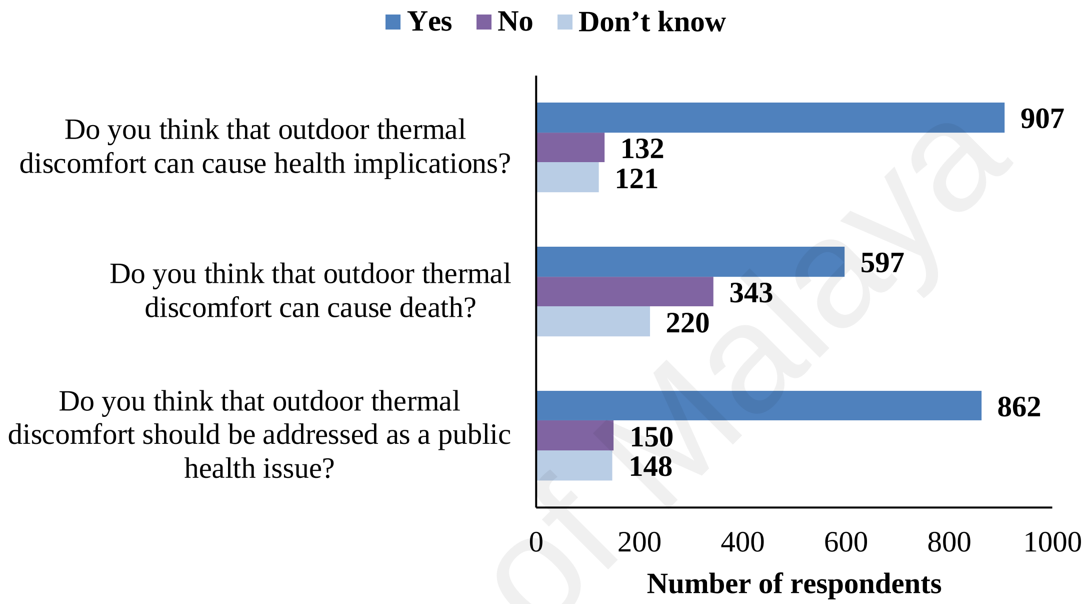


Figure 4.20: Outdoor thermal discomfort as a public health issue

A majority (n=907, 78.2%) agreed that the outdoor thermal discomfort would have an impact on human health. However, only 51.5% (n=597) of the respondents think that the thermal discomfort could cause death while 29.6% (n=343) of the respondents do not agree that the deterioration in OTC could cause death. Lastly, the respondents were asked if the outdoor thermal discomfort should be addressed as a public health issue and a majority (n=862, 74.3%) agreed that it should be considered while 25.7% (n=298) were either against it or unsure about it.

Due to a changing climate, it was postulated that by 2050, deaths from heatwaves could reach 260,000 individuals annually while heat-related work-hour losses in some Asian and African countries could account for billions of US dollars in lost productivity (Global Clean Cooling Landscape Assessment, 2018). In a review, Ramakreshnan et al. (2017) highlighted the evidence of physical and psychological health impacts of haze in ASEAN countries (Ramakreshnan et al., 2017). Unlike health issues due to transboundary haze, the relationship between health issue and the urban thermal environment has remained unexplored especially in the tropical region of SEA countries despite having evidence such as a significant reduction in cognitive functions during hot periods (Global Clean Cooling Landscape Assessment, 2018). The findings from this study are in hope to provide evidence to stakeholders on the importance of climate literacy towards fostering a climate-resilient community.

4.4.5 Summary

In summary, human health complications (distinguished according to physical, psychosomatic and psychological health) that arise due to the urban heat is explored in this study. In general, a majority of the urban community were found to have low severity of physical health impact (n=819, 74.2%), psychosomatic health impact (n=693, 65.9%), anxiety (n=931, 84.6%) and depression (n=799, 73.0%).

Heat exhaustion was found to be the most reported physical symptom with about half (n=569, 49.2%) of the respondents reported of experiencing it. Tiredness was found to be the most reported psychosomatic symptom with 77.0% (n=891) of the respondents reported experiencing it. Besides, psychosomatic symptoms such as trouble sleeping (n=769, 66.5%) and headache (n=684, 59.1%) were also experienced by more than half of the respondents. In terms of anxiety-related psychological health symptoms, commonly reported symptoms are feeling nervous (n=518, 44.8%), trouble relaxing (n=509, 44.0%) and being easily annoyed (n=471, 40.7%). Meanwhile, commonly reported depression-related psychological health symptoms are feeling tired (n=872, 75.4%), little interest in doing things (n=717, 62.0%), poor appetite or overeating (n=715, 61.8%), trouble falling or staying asleep (n=708, 61.2%) and trouble with concentrating at home, school, work or while doing other things (n=674, 58.3%).

Through EFA, physical health is clustered into two health components which are sensory organ pain (5 items) and heat-related illnesses (4 items) while psychosomatic health is clustered into three health components which are cardiopulmonary (6 items), pain (5 items) and fatigue (2 items) related symptoms. In terms of psychological health, the three health components identified were anxiety (7 items), somatization (5 items) and depression (4 items) related symptoms. Urban heat significantly affected pain-related psychosomatic symptoms (p=0.016), as well as psychological health in terms of anxiety (p=0.022) and somatization (p=0.041) related symptoms. Other health components were found to be not significantly associated with urban heat.

It was also found that confounding factors such as gender, age group, ethnicity and duration of exposure at outdoors in a day have varying influence towards the health outcomes. More studies are needed to unravel the influence of these confounding factors besides conducting subject-specific studies involving vulnerable and sensitive population. Future research direction should also consider conducting longitudinal studies which may be beneficial in unravelling the long-term impact of urban heat exposure towards the health and well-being of urban communities in a tropical city.

4.5 Phase 3: Development and validation of 3D urban microclimate model of study area

Section 4.5 is allocated to present the findings to address the third objective of the study which is to develop and validate a 3D UMM of the study area. In the first sub-section, the development of the UMM in ENVI-MET software is presented. The following sub-sections are allocated to present the validation of the UMM as a reliable tool for the simulation of urban microclimate in the study area.

4.5.1 Developing the 3D urban microclimate model of selected study area

The analysis has been carried out to develop a model of the selected study area with a dimension of 400 m by 400 m. The morphology of the selected study area consisting of points, lines and polygons are extracted from OSM and Google Earth into the world of ENVI-MET Monde before exporting to ENVI-MET Spaces for 3D modelling. The aerial view of the urban model is presented in Figure 4.21.

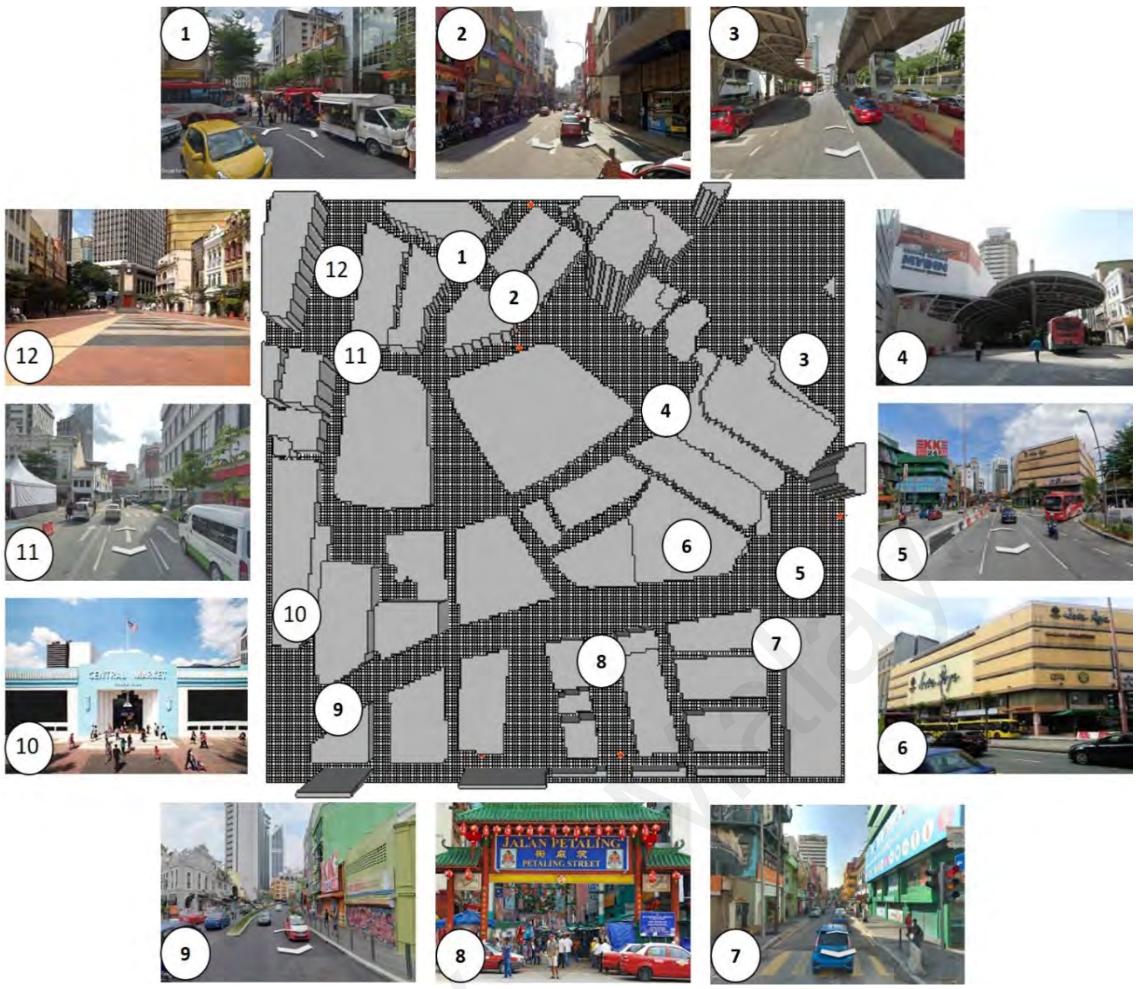


Figure 4.21: Aerial view of the urban model

The area has been rendered with a 200 x 200 x 25 (x-y-z) grids. The length (dx), width (dy) and height (dz) of each grid represent 5 m respectively. The resolution chosen is well within the suitable range of ENVI-MET software, i.e., 0.5 m to 10 m. On top of that, the resolution is a reasonable compromise between accuracy and computation time. Figure 4.22 is the view of the study area at 45° inclinations.

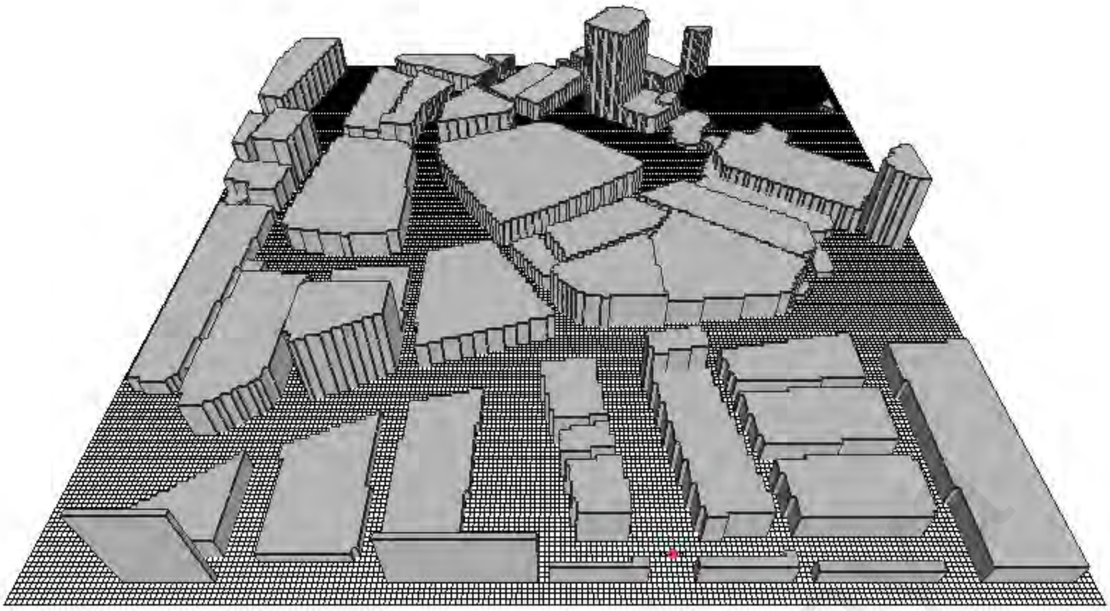


Figure 4.22: 3D urban microclimate model of selected study area at 45° inclinations

There are 40 buildings in the study area. The highest building in the domain is 60 m while the lowest building is 3 m. The mean building height in the domain is 17 m or about 6 floors (1 floor approximately 3 m in height). To achieve a stable numerical UMM, the maximum height of the domain must be at least twice the height of the highest building with elevation, i.e., 60 m in this study. As the domain does not violate the rules to achieve numeric stability, no telescoping factor at the z-axis was applied. The influence of the edge effects for the z-plane is assumed to be negligible. However, on the horizontal scale of x-plane and y-plane, 5 nesting grids were allocated to the model edges to allow a more stable and accurate simulation. The validation of the UMM is presented in the next sub-section.

4.5.2 Validation of urban microclimate model

Validation is an important step in scientific research to ensure the reliability of findings especially when it comes to simulation and modelling approaches. Salata et al. (2016) suggested that the predictive ability of the ENVI-MET software needs to be testified for Ta and Tmrt (Salata et al., 2016). However, since Tmrt is not measured but estimated in this study, only Ta data was included for validation purposes. On top of what was suggested, the simulated RH, WS and SR data were also extracted and compared with ground measurements in the study area. The resemblance of both simulated and observed dataset will determine the efficiency of ENVI-MET in simulating the microclimate data. Two different data sets of microclimate observations were used in the validation process to investigate the robustness of the simulation model to predict microclimate variations. The validation findings are presented in the subsequent sections.

4.5.2.1 Validation of hourly average microclimate variation with yearly data

A Pearson correlation analysis is conducted to identify the strength of the association between the observed and simulated microclimate parameters. The hourly average of observed microclimate data from AWS from January 2018 to December 2018 was identified and associated with the simulated microclimate data from ENVI-MET. The descriptive statistics of the observed and simulated microclimate parameters, as well as the correlation results, are summarized in Table 4.42.

Table 4.42: Descriptive statistics and correlation between observed and simulated microclimate parameters according to yearly data

Meteorological parameters	Observed		Simulated		Correlation, r
	Mean	SD	Mean	SD	
Ta (°C)	31.22	1.46	31.48	2.16	0.881**
RH (%)	62.99	7.56	59.33	8.49	0.951**
WS (m/s)	1.12	0.45	0.56	0.03	0.490*
SR (W/m^2)	221.89	163.67	340.26	452.95	0.950**

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

The difference between observed and simulated data was found to be minimal for Ta with 0.26°C and RH with 3.66%. On the contrary, the difference for observed and simulated WS and SR data were found to be slightly larger at 0.56 m/s and 118.37 W/m^2, respectively. In general, all association between the observed and simulated microclimate data were found to be significant at p=0.01 level (2-tailed) except for the observed and simulated WS which is significant at p=0.05 level (2-tailed). There is a strong and positive correlation for observed and simulated Ta (r=0.881, n=24, p<0.0.1), RH (r=0.951, n=24, p<0.0.1) and SR (r=0.950, n=24, p<0.0.1). One of the possible explanations for the strong association can be attributed to the simple radiative forcing function within ENVI-MET software that allows the user to customize the hourly variation of Ta and RH in the simulation model. In comparison, the UMM in this study can show similar replicability of actual microclimate variations as shown in the remote sensing model that evaluated ambient temperature by Ibrahim et al. (2014). Interestingly, the simulation of SR variation was also found to be exceptionally good despite not being able to customize the hourly variations through the simple radiative forcing function. Meanwhile, the association between the observed and simulated WS was found to show positive and moderate correlation (r=0.490, n=24, p<0.0.1). The larger difference in observed and simulated WS is expected because the variations in WS is much complex as it deals with resultant vectors happening at instantaneous moments. Nonetheless, the simulated WS shows promising reliability as supported by moderate correlation with observational data.

In short, the yearly microclimate data were found to be suitable drivers in ENVI-MET simulation model. In particular, the simulated Ta, RH and SR were exceptionally accurate while WS data were moderately accurate. In further analysis, the validation of the ENVI-MET model is repeated to identify the reliability of ENVI-MET in simulating daily microclimate variation for selected days with full 24-hour microclimate observations.

4.5.2.2 Validation of hourly average microclimate variation with daily data

In continuation, the ENVI-MET model is also tested to see if it is reliable to simulate urban microclimate variations using daily data. Instead of using average hourly data across a year, randomly selected days which recorded continuous 24 hours' meteorological data were included for this validation process. A Pearson correlation analysis is conducted to identify the strength of the association between the observed and simulated microclimate parameters. The descriptive statistics of the observed and simulated microclimate parameters, as well as the correlation results, are summarized in Table 4.43.

Table 4.43: Descriptive statistics and correlation between observed and simulated microclimate parameters according to daily data

Meteorological parameters	Observed		Simulated		Correlation, r
	Mean	SD	Mean	SD	
Ta (°C)	32.29	2.30	32.88	1.36	0.159
RH (%)	61.31	6.13	57.15	4.88	0.286
WS (m/s)	0.92	0.32	0.35	0.01	-0.164
SR (W/m^2)	221.33	160.16	346.33	446.08	-0.827^{**}

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

The difference between observed and simulated data was found to be minimal for Ta with 0.59°C and RH with 4.16%. On the contrary, the difference for observed and simulated WS and SR data were found to be slightly larger at 0.57 m/s and 125.00 W/m^2, respectively. In terms of replicability of actual microclimate conditions, the UMM did not perform well to simulate microclimate variations using daily data. The only strong and significant association was found between the observed and simulated SR ($r=0.827$, $n=24$, $p<0.01$). On the other hand, the association between the observed and simulated Ta ($r=0.159$, $n=24$, $p>0.01$), RH ($r=0.286$, $n=24$, $p>0.01$) and WS ($r= -0.164$, $n=24$, $p>0.01$) were all weak and insignificant. One of the possible explanations for the weak association could be related to the complex interaction between the built and natural environment in the study area combined with the dynamic daily microclimate variations. Therefore, daily microclimate data are considered to be poor drivers in ENVI-MET simulation model.

4.5.3 The reliability of urban microclimate model for microclimate simulation

The UMM representing the selected study area was successfully developed and validated with two sets of data representing yearly and daily average microclimate data. In short, the UMM was found to be more accurate and reliable to simulate microclimate variations using data from long period average as compared to daily average data. Although the weak association for daily microclimate simulation is postulated to be influenced by the complex micro-interaction between the built and natural environment, more studies are needed to provide the necessary scientific evidence which is lacking in the current study. Nevertheless, the reliability of ENVI-MET found through this study agreed with the results from Yang et al., (2016), Yang et al. (2016), Yang & Lin (2016), Yang et al., (2015) and Qaid et al. (2016) (Qaid et al., 2016; Yang et al., 2016; Yang & Lin, 2016; Yang et al., 2016, 2015). Although there is negligible variance among the simulated and measured data, it is agreed that ENVI-MET is a promising research tool for UHI and OTC studies in a tropical city such as KL.

The findings in this section suggest that ENVI-MET is capable of dealing with stable long period microclimate variations much better as compared to day-to-day dynamic-complex instantaneous variations. Hence, ENVI-MET users need to be cautious in selecting meteorological data for the simulation in ENVI-MET software. In particular, extra consideration is needed to select an appropriate time frame of data during the preparation of the simulation profile. Future studies can also identify the optimum time-weighted average of meteorological data which could bring a more precise urban microclimate simulation.

Considering the continual advancement in technology, an integrated approach using remote sensing and GIS techniques can be used to determine and extrapolate land surface temperature covering a large area (Ibrahim & Samah, 2011). However, there are mainly two advantages of current microclimate modelling as compared to remote sensing approach. Firstly, the resolution of the UMM in this study (which is 2 m by 2 m) will be able to evaluate the microclimate variations in a much precise manner. In contrast, remote sensing data is larger in terms of pixel size. For example, the pixel size is 1 km by 1 km for data images provided by MODIS (Ibrahim et al., 2017). Comparatively, the UMM will be able to simulate up to 250,000 times more precise as compared to satellite imageries from MODIS with proven accuracy. Secondly, the UMM can simulate the microclimate variations near-surface level at 2 m height. The Landsat image which consists of seven spectral bands from Nordin et al., (2017) is only capable of showing a horizontal spatial resolution of 30 m pixels from the surface (Nordin et al., 2017). Although the higher resolution of satellite imageries can be acquired, these data sets would be costly. Nonetheless, the integrated approach of remote sensing and GIS can be further explored to complement the current validation approach in this study where field investigations are not easy and time-consuming. The findings from simulating urban heat mitigation measures to improve the urban microclimate are presented in the following section.

4.6 Phase 3: Urban heat mitigation measures via urban microclimate simulation

In previous Section 4.5, a UMM of the selected study area is developed and validated to be a reliable microclimate simulation tool. In continuation, few UHI mitigation measures to improve the urban microclimate were explored and the findings are presented in this section.

4.6.1 Initial simulation of urban microclimate variations in the study area

From the developed UMM in Section 4.5, the area and dimension of the simulated UMM were scaled down by a factor of 4 from 0.16 km^2 (400 m by 400 m) to 0.04 km^2 (200 m by 200 m) due to the limitation in both hardware and software capabilities. The thermal map of the microclimate simulation at an interval of 4 hours from 8.00 am to 4.00 am in the study area is presented in Figure 4.23, while the average of simulated microclimate data from the UMM is extracted and summarized in Table 4.44.

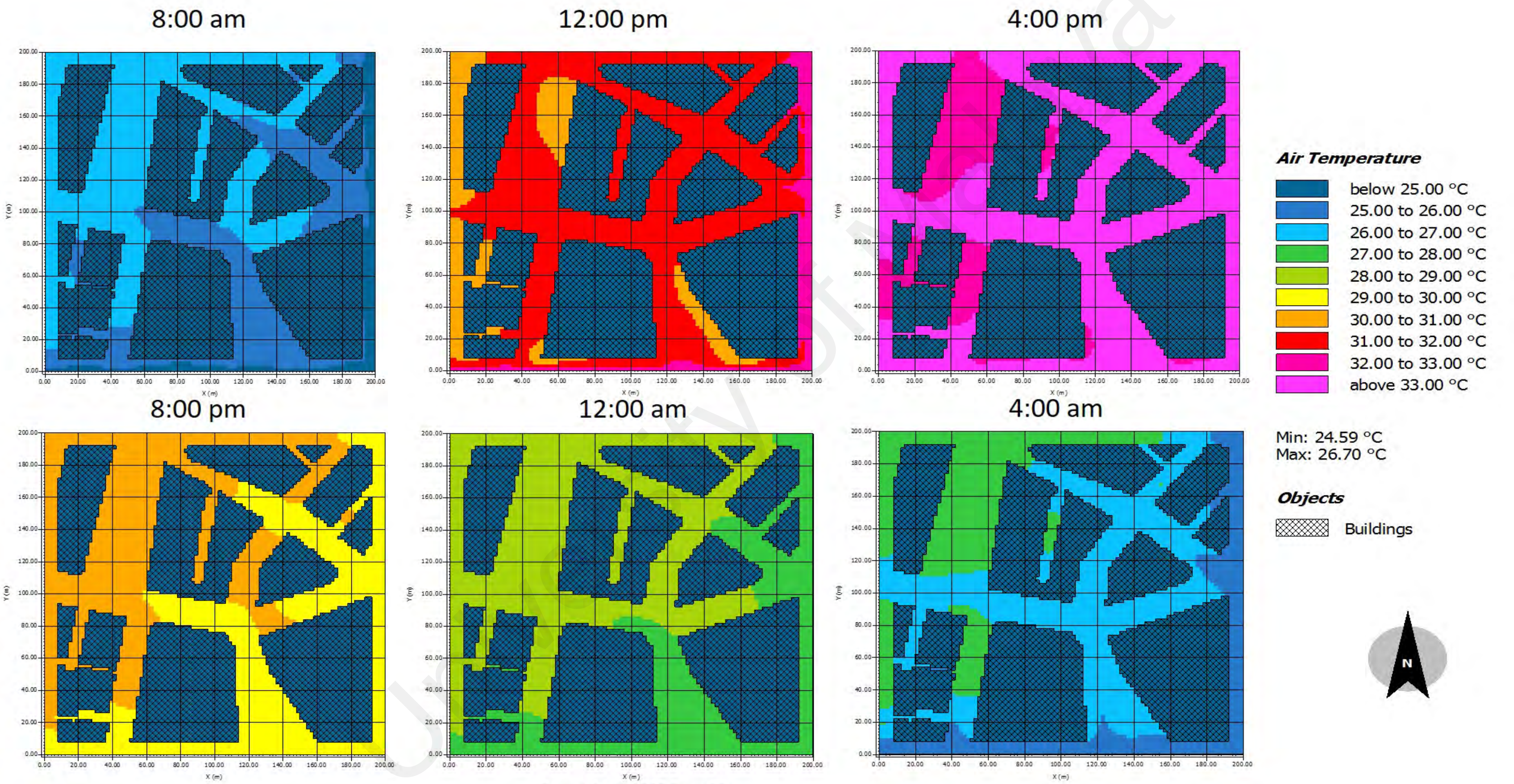


Figure 4.23: Simulation of air temperature at selected study area from 8:00 am to 4:00 am

Table 4.44: The average of simulated microclimate variations in the urban microclimate model

Time	WS	Ta	RH	Tmrt
8:00	0.64	26.04	77.16	16.60
9:00	0.63	27.33	71.85	45.14
10:00	0.61	29.00	64.93	62.88
11:00	0.60	30.33	58.52	65.62
12:00	0.60	31.37	53.84	65.49
13:00	0.60	32.33	50.32	65.67
14:00	0.59	33.18	47.45	68.78
15:00	0.58	33.74	45.67	72.58
16:00	0.58	33.56	46.25	56.50
17:00	0.57	32.85	47.69	51.16
18:00	0.57	31.98	50.99	34.90
19:00	0.57	30.79	55.59	25.24
20:00	0.57	29.88	59.59	22.49
21:00	0.58	29.28	62.31	21.07
22:00	0.58	28.83	64.46	20.10
23:00	0.58	28.47	66.14	19.40
0:00	0.58	28.15	67.42	18.83
1:00	0.58	27.53	70.79	18.05
2:00	0.58	27.18	72.17	17.55
3:00	0.58	26.89	73.03	17.13
4:00	0.58	26.64	73.78	16.77
5:00	0.58	26.43	74.42	16.47
6:00	0.58	26.22	75.00	16.18
7:00	0.58	26.06	75.18	15.98

The mean and standard deviation of the microclimate variations are summarized in Table 4.45.

Table 4.45: The mean and standard deviation of simulated microclimate variations in the urban microclimate model

Meteorological parameters	Mean	Standard Deviation
Ta (°C)	26.04	2.60
RH (%)	71.85	10.69
WS (m/s)	0.61	0.02
Tmrt (°C)	65.62	21.64

Further validation was not conducted at this stage as it has been fully covered previously in Section 4.5. In subsequent analysis, the urban hotspot is identified from the UMM.

4.6.2 Identifying urban hotspots

Urban hotspots are identified as areas which are found to have a slower heat dissipation rate as compared to the other simulated regions in the UMM. According to Figure 4.24, the urban hotspot in the study area was identified to be in the upper left quadrant of the UMM. The urban hotspot in the study area resembles an urban canyon layout where the open space is surrounded by two buildings at both right and left side. The height of the building at right is about 9 m tall while the building at the left is 25 m tall. These two buildings are commercial shop lots accommodating banks, restaurants, groceries stalls and other offices. Meanwhile, the open space within the hotspot serves as a common space for leisure activities and also function as a passage from train stations to nearby tourist attraction spots such as Central Market, Chinatown at Petaling Street, Masjid Jamek Mosque and Merdeka Square. Hawker stalls are also commonly found in the open space area selling food and beverages. In further analysis, various urban heat mitigation measures were carried out through ENVI-MET to identify their effectiveness in improving the urban microclimate of the identified hotspot.

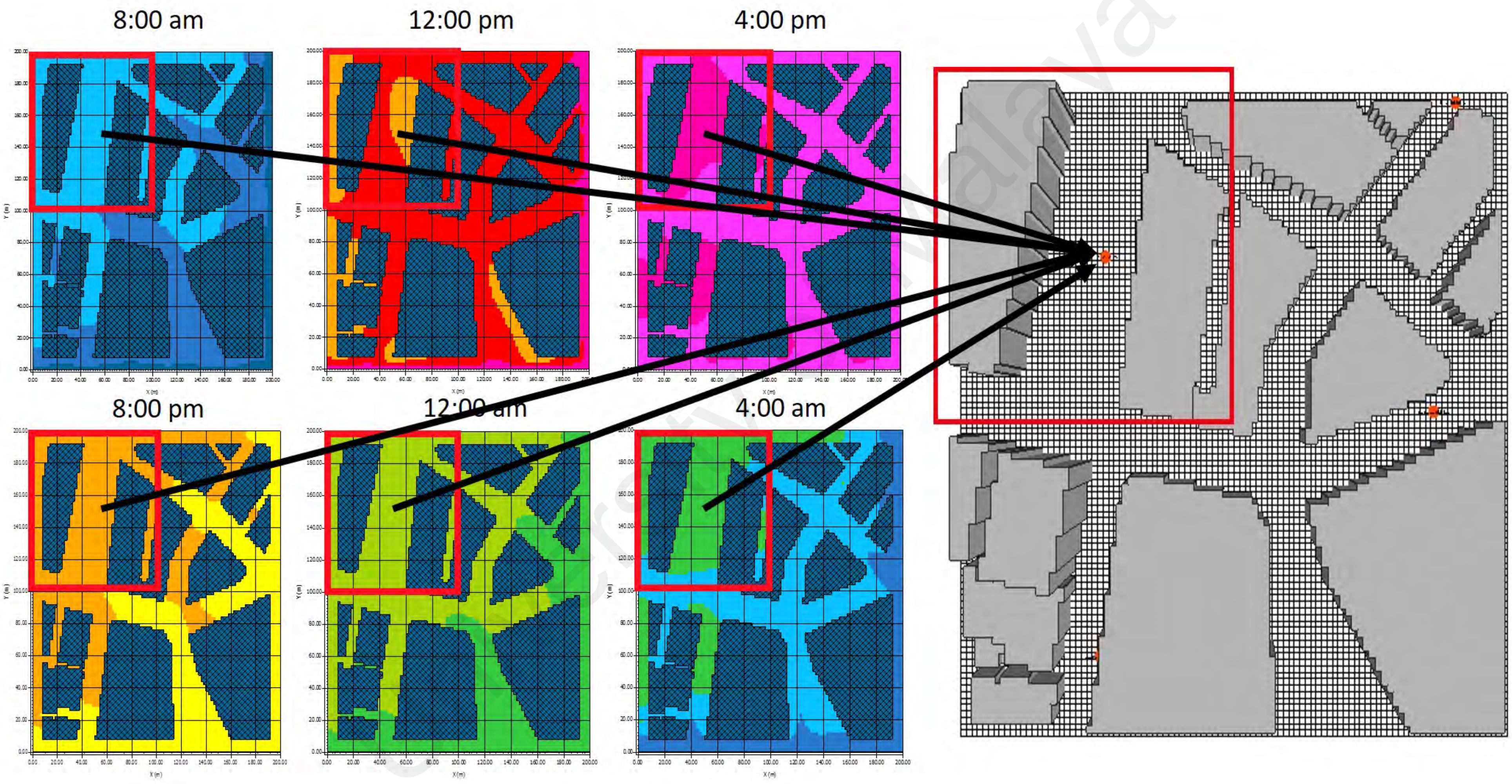
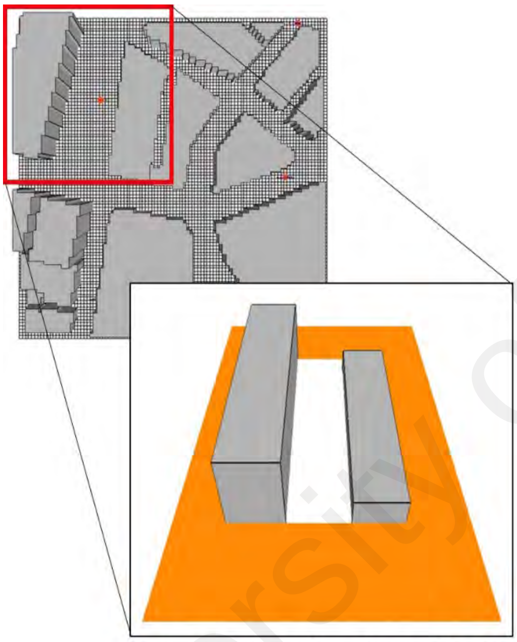


Figure 4.24: The identified urban hotspot in the urban microclimate model

4.6.3 Simulating the urban heat mitigation performance

Based on the urban hotspot identified in Section 4.6.2, further urban heat mitigation analysis is simulated. The model was redeveloped considering the limitation in both hardware and software to execute stable microclimate simulation. The model is rotated about -10 degrees to facilitate the development of UMM according to the squared grids. The urban hotspot which is also the control case study is known here as the default UMM. The model geometry of the default UMM is presented in Figure 4.25.



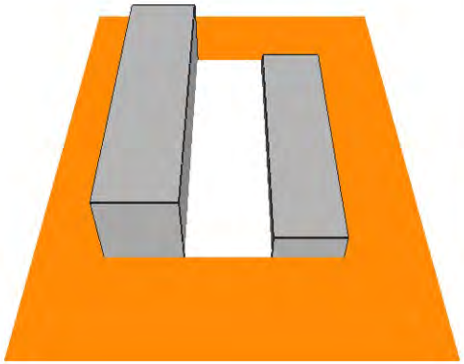
Default Urban Microclimate Model

Model geometry	Area (%)
Building coverage	21.6
Grass and tree coverage	0.0
Open space with grey concrete pavement	13.2
Green façade coverage	0.0
Green roof coverage	0.0
Other open space	38.5
Nesting grid	26.7
Total	**100.00**

Figure 4.25: The default urban microclimate model for urban heat mitigation analysis

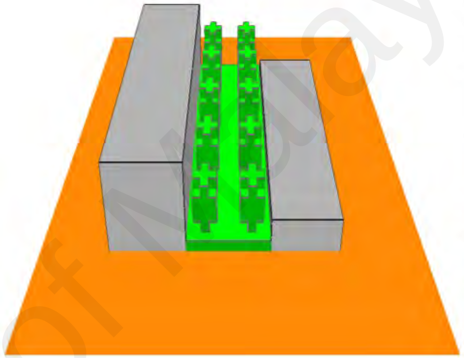
Meanwhile, the model geometry for the other four case scenarios which are Cool Pavement Model (CPM), Urban Vegetation Model (UVM), Green Façade Model (GFM) and Green Roof Model (GRM) are summarized in Figure 4.26. The microclimate simulation was performed for each case scenario and the simulated microclimate data was extracted. The findings are presented in subsequent sections.

Case scenario 1: CPM



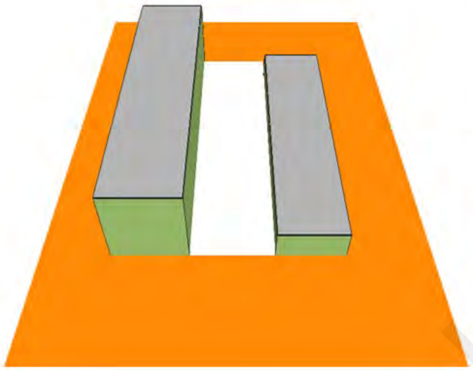
Model geometry	Area (%)
Building coverage	21.6
Grass and tree coverage	0.0
Open space with light concrete pavement	13.2
Green façade coverage	0.0
Green roof coverage	0.0
Other open space	38.5
Nesting grid	26.7
Total	**100.00**

Case scenario 2: UVM



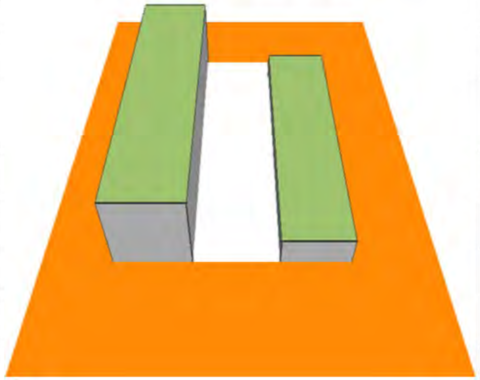
Model geometry	Area (%)
Building coverage	21.6
Grass and tree coverage	13.2
Open space with grey concrete pavement	0.0
Green façade coverage	0.0
Green roof coverage	0.0
Other open space	38.5
Nesting grid	26.7
Total	**100.00**

Case scenario 3: GFM



Model geometry	Area (%)
Building coverage	21.6
Grass and tree coverage	0.0
Open space with grey concrete pavement	13.2
Green façade coverage	35.8
Green roof coverage	0.0
Other open space	38.5
Nesting grid	26.7
Total	**100.00**

Case scenario 4: GRM



Model geometry	Area (%)
Building coverage	21.6
Grass and tree coverage	0.0
Open space with grey concrete pavement	13.2
Green façade coverage	0.0
Green roof coverage	21.6
Other open space	38.5
Nesting grid	26.7
Total	**100.00**

Figure 4.26: Summary of case scenario for urban heat mitigation analysis

4.6.3.1 Simulated microclimate data for default urban microclimate model

The simulated microclimate data from the default UMM is extracted and the hourly average for WS, Ta, RH and Tmrt was identified. The hourly average simulated microclimate data are presented in Table 4.46.

Table 4.46: Average simulated microclimate data for default urban microclimate model

Time	WS (m/s)	Ta (ºC)	RH (%)	Tmrt (ºC)
8:00	1.74	27.48	73.95	18.92
9:00	1.75	28.72	68.14	48.39
10:00	1.74	29.84	62.75	65.21
11:00	1.75	30.72	58.72	67.09
12:00	1.76	31.54	55.39	66.50
13:00	1.77	32.17	53.09	66.17
14:00	1.77	32.63	51.64	69.53
15:00	1.78	32.87	51.27	74.18
16:00	1.78	32.47	52.09	58.87
17:00	1.78	31.86	55.08	45.23
18:00	1.78	30.98	58.64	35.87
19:00	1.79	30.06	62.80	23.82
20:00	1.79	29.54	65.38	21.99
21:00	1.81	29.15	67.43	21.08
22:00	1.82	28.83	69.05	20.47
23:00	1.83	28.54	70.32	19.98
0:00	1.84	27.89	73.99	19.17
1:00	1.84	27.56	75.40	18.71
2:00	1.85	27.28	76.34	18.31
3:00	1.85	27.04	77.15	17.99
4:00	1.86	26.84	77.87	17.72
5:00	1.86	26.62	78.55	17.44
6:00	1.86	26.47	78.79	17.23
7:00	1.86	26.65	77.94	17.36

Meanwhile, the mean and standard deviation of the simulated microclimate data is summarized in Table 4.47.

Table 4.47: The mean and standard deviation of simulated microclimate in the default urban microclimate model

Parameters	Mean	Standard Deviation
Ta (°C)	27.48	2.15
RH (%)	68.14	9.84
WS (m/s)	1.74	0.04
Tmrt (°C)	67.09	21.83

The simulated microclimate data from the default UMM is chosen to be the baseline for comparison with other urban heat mitigation measures from the other four case scenarios.

4.6.3.2 Simulated microclimate data for case scenario 1: Cool Pavement Model (CPM)

In the first case scenario, the default UMM is modified into the CPM as shown in Figure 4.27. The model is modified by considering the replacement of the pavement material which make up the open space in the urban hotspot. The existing grey concrete pavement with an albedo of 0.5 is replaced with a light concrete pavement with a higher albedo of 0.8. The emissivity of the surface remains at 0.9 while no other changes were implied to the UMM.

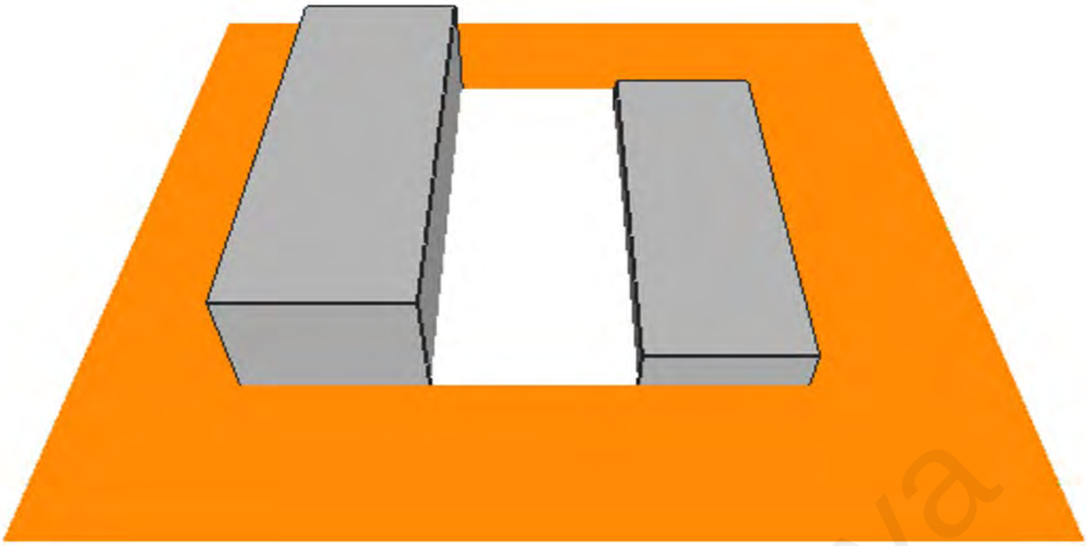


Figure 4.27: Cool pavement model (CPM)

The hourly simulated microclimate data extracted for the CPM are presented in Table 4.48, and the mean and standard deviation of the simulated microclimate data are summarized in Table 4.49.

Table 4.48: Average simulated microclimate data for cool pavement model

Time	WS (m/s)	Ta (ºC)	RH (%)	Tmrt (ºC)
8:00	1.74	27.49	73.90	18.97
9:00	1.75	28.70	68.20	49.63
10:00	1.75	29.76	62.96	67.50
11:00	1.75	30.62	58.99	70.35
12:00	1.77	31.41	55.75	70.52
13:00	1.78	31.99	53.59	70.57
14:00	1.78	32.37	52.35	73.26
15:00	1.78	32.54	52.20	76.87
16:00	1.78	32.26	52.68	60.81
17:00	1.79	31.82	55.17	46.41
18:00	1.79	31.01	58.53	36.54
19:00	1.79	30.15	62.49	24.16
20:00	1.80	29.63	65.05	22.29
21:00	1.81	29.23	67.10	21.39
22:00	1.82	28.92	68.72	20.78
23:00	1.83	28.62	69.99	20.28
0:00	1.84	27.98	73.62	19.47
1:00	1.84	27.65	75.03	19.01
2:00	1.85	27.36	75.97	18.61
3:00	1.85	27.12	76.79	18.28
4:00	1.85	26.92	77.52	18.00
5:00	1.85	26.70	78.20	17.72
6:00	1.85	26.55	78.44	17.51
7:00	1.85	26.73	77.62	17.63

Table 4.49: The mean and standard deviation of simulated microclimate in the cool pavement model

Parameters	Mean	Standard Deviation
Ta (ºC)	27.49	2.05
RH (%)	68.20	9.50
WS (m/s)	1.75	0.04
Tmrt (ºC)	70.35	23.13

The simulated microclimate data from the CPM are later compared to the default UMM and other urban heat mitigation measures in Section 4.6.4.

4.6.3.3 Simulated microclimate data for case scenario 2: Urban Vegetation Model (UVM)

In the second case scenario, the default UMM is modified into the UVM as shown in Figure 4.28. The model is modified by considering the replacement of the pavement material which make up the open space in the urban hotspot. The existing grey concrete pavement is replaced with loamy soils containing vegetation which comprises of short grass and trees. According to the Green Index, the grass and tree coverage occupies about 15% or 1,500 m^2 of the urban hotspot.

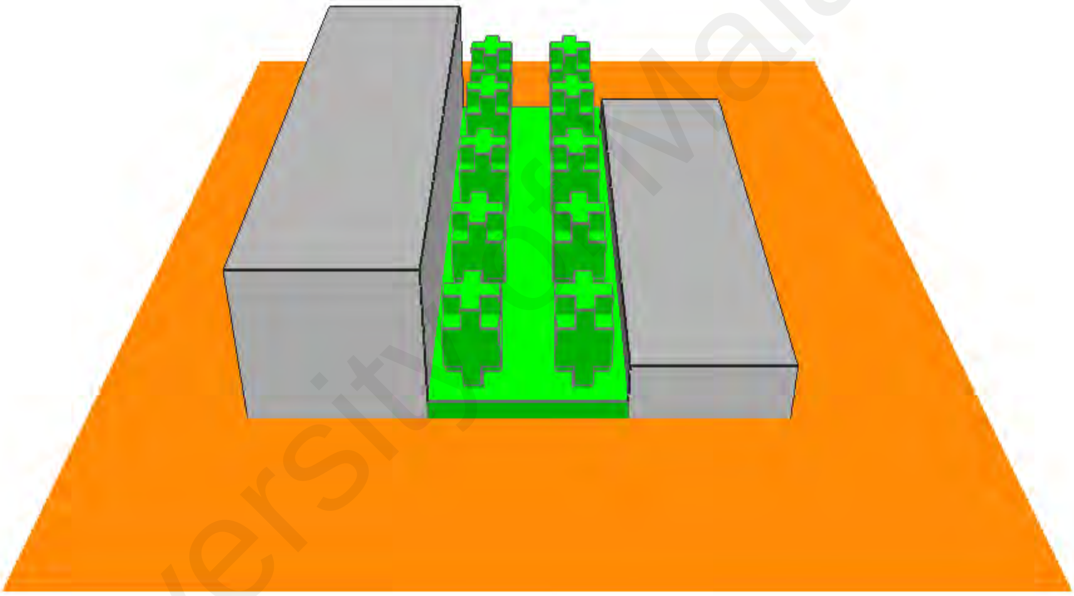


Figure 4.28: Urban vegetation model (UVM)

The hourly simulated microclimate data extracted for the UVM are presented in Table 4.50.

Table 4.50: Average simulated microclimate data for urban vegetation model

Time	WS (m/s)	Ta (ºC)	RH (%)	Tmrt (ºC)
8:00	1.08	27.28	74.90	22.90
9:00	1.07	28.58	69.25	35.41
10:00	1.06	29.78	63.77	50.34
11:00	1.06	30.75	59.49	55.08
12:00	1.06	31.67	55.86	58.97
13:00	1.06	32.39	53.27	55.20
14:00	1.06	32.88	51.67	58.25
15:00	1.06	33.15	51.21	66.42
16:00	1.06	32.74	52.09	63.64
17:00	1.05	31.89	55.74	40.83
18:00	1.05	30.88	59.52	33.57
19:00	1.05	29.95	63.33	24.79
20:00	1.05	29.41	65.93	23.47
21:00	1.05	29.00	68.05	22.74
22:00	1.05	28.68	69.71	22.23
23:00	1.06	28.39	71.01	21.81
0:00	1.06	27.73	74.75	21.08
1:00	1.06	27.39	76.20	20.65
2:00	1.05	27.11	77.16	20.29
3:00	1.05	26.87	78.00	19.99
4:00	1.04	26.66	78.74	19.74
5:00	1.04	26.44	79.44	19.48
6:00	1.03	26.28	79.69	19.29
7:00	1.03	26.46	78.84	19.40

The mean and standard deviation of the simulated microclimate data are summarized in Table 4.51.

Table 4.51: The mean and standard deviation of simulated microclimate in the urban vegetation model

Parameters	Mean	Standard Deviation
Ta (ºC)	27.28	2.30
RH (%)	69.25	10.08
WS (m/s)	1.06	0.01
Tmrt (ºC)	55.08	17.01

The simulated microclimate data from the UVM are later compared to the default UMM and other urban heat mitigation measures in Section 4.6.4.

4.6.3.4 Simulated microclimate data for case scenario 3: Green Façade Model (GFM)

In the third case scenario, the default UMM is modified into the GFM as shown in Figure 4.29. The model is modified by adding green façade to the existing wall of the two buildings located in the urban hotspot. Greeneries with sandy loam substrates are added to all wall sides of the building while other urban model geometries remain unchanged. According to the wall surface area of the two buildings, the total green façade occupies about 35.8% in the urban hotspot.

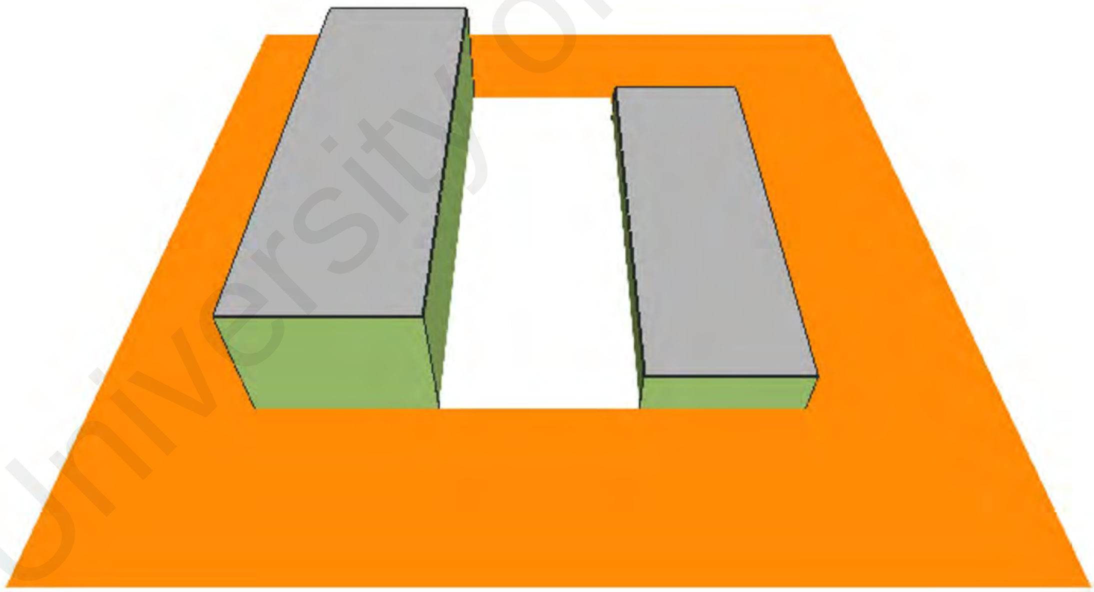


Figure 4.29: Green façade model (GFM)

The hourly simulated microclimate data extracted for the GFM is presented in Table 4.52.

Table 4.52: Average simulated microclimate data for green façade model

Time	WS (m/s)	Ta (ºC)	RH (%)	Tmrt (ºC)
8:00	1.74	27.49	73.90	18.95
9:00	1.75	28.72	68.14	49.08
10:00	1.75	29.86	62.62	66.55
11:00	1.75	30.84	58.31	69.01
12:00	1.76	31.72	54.82	68.83
13:00	1.77	32.37	52.51	68.65
14:00	1.78	32.78	51.20	71.57
15:00	1.78	32.93	51.08	75.64
16:00	1.78	32.58	51.77	59.99
17:00	1.78	32.03	54.55	46.04
18:00	1.78	31.16	58.03	36.46
19:00	1.79	30.26	62.12	24.31
20:00	1.80	29.70	64.77	22.44
21:00	1.80	29.29	66.88	21.51
22:00	1.82	28.97	68.54	20.88
23:00	1.83	28.66	69.84	20.37
0:00	1.83	28.01	73.48	19.55
1:00	1.84	27.68	74.91	19.07
2:00	1.84	27.39	75.86	18.67
3:00	1.85	27.15	76.70	18.34
4:00	1.85	26.94	77.43	18.06
5:00	1.85	26.72	78.12	17.77
6:00	1.85	26.56	78.36	17.55
7:00	1.85	26.74	77.56	17.67

The mean and standard deviation of the simulated microclimate data are summarized in Table 4.53.

Table 4.53: The mean and standard deviation of simulated microclimate in the green façade model

Parameters	Mean	Standard Deviation
Ta (ºC)	27.49	2.17
RH (%)	68.14	9.85
WS (m/s)	1.75	0.04
Tmrt (ºC)	69.01	22.48

The simulated microclimate data from the GFM is later compared to the default UMM and other urban heat mitigation measures in Section 4.6.4.

4.6.3.5 Simulated microclimate data for case scenario 4: Green Roof Model (GRM)

In the fourth case scenario, the default UMM is modified into the GRM as shown in Figure 4.30. The model is modified by adding greeneries to the roof of the two buildings located in the urban hotspot. Greeneries with sandy loam substrates are added to the roof of the two buildings while other urban model geometries remain unchanged. According to the roof surface area of the two buildings, the total green roof occupies about 21.6% in the urban hotspot.

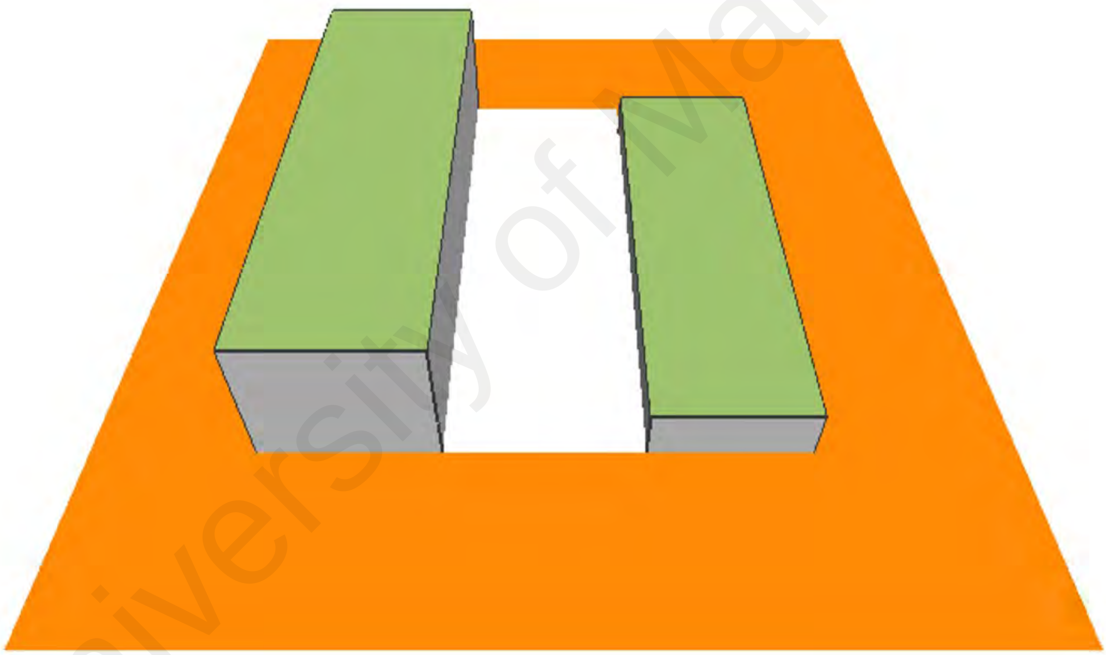


Figure 4.30: Green roof model (GRM)

The hourly simulated microclimate data extracted for the GRM is presented in Table 4.54.

Table 4.54: Average simulated microclimate data for green roof model

Time	WS (m/s)	Ta (ºC)	RH (%)	Tmrt (ºC)
8:00	1.77	27.49	73.93	23.03
9:00	1.77	28.72	68.13	49.16
10:00	1.77	29.87	62.61	66.62
11:00	1.77	30.84	58.29	69.04
12:00	1.79	31.72	54.80	68.79
13:00	1.79	32.37	52.48	68.53
14:00	1.80	32.79	51.17	71.45
15:00	1.80	32.94	51.05	75.58
16:00	1.80	32.59	51.75	60.00
17:00	1.80	32.05	54.50	46.13
18:00	1.81	31.17	58.01	36.56
19:00	1.81	30.26	62.11	24.32
20:00	1.82	29.70	64.78	22.42
21:00	1.83	29.29	66.89	21.48
22:00	1.84	28.96	68.56	20.85
23:00	1.85	28.66	69.86	20.34
0:00	1.86	28.01	73.50	19.52
1:00	1.87	27.67	74.93	19.04
2:00	1.87	27.38	75.88	18.64
3:00	1.87	27.14	76.72	18.31
4:00	1.88	26.93	77.45	18.03
5:00	1.88	26.72	78.14	17.74
6:00	1.88	26.56	78.39	17.52
7:00	1.88	26.74	77.58	17.64

The mean and standard deviation of the simulated microclimate data are summarized in Table 4.55.

Table 4.55: The mean and standard deviation of simulated microclimate in the green roof model

Parameters	Mean	Standard Deviation
Ta (ºC)	27.49	2.18
RH (%)	68.13	9.87
WS (m/s)	1.77	0.04
Tmrt (ºC)	69.04	22.35

The simulated microclimate data from the GRM is later compared to the default UMM and other urban heat mitigation measures in Section 4.6.4.

4.6.4 Comparison of urban heat mitigation measures towards the improvement of urban microclimate

The simulated microclimate data extracted from each urban heat mitigation model from section 4.6.3 is compared to the microclimate data from default UMM to identify the efficacy of each model in improving the urban microclimate. The findings according to each microclimate variables are presented in the following sub-section.

4.6.4.1 Air temperature

The hourly Ta simulated from each model are presented in Table 4.56, while the variations of Ta against time are plotted in Figure 4.31.

Table 4.56: Comparison of simulated air temperature according to case scenarios

	Air temperature (°C)				
Time	**UMM**	**UVM**	**CPM**	**GFM**	**GRM**
8:00	27.48	27.28	27.49	27.49	27.49
9:00	28.72	28.58	28.70	28.72	28.72
10:00	29.84	29.78	29.76	29.86	29.87
11:00	30.72	30.75	30.62	30.84	30.84
12:00	31.54	31.67	31.41	31.72	31.72
13:00	32.17	32.39	31.99	32.37	32.37
14:00	32.63	32.88	32.37	32.78	32.79
15:00	32.87	33.15	32.54	32.93	32.94
16:00	32.47	32.74	32.26	32.58	32.59
17:00	31.86	31.89	31.82	32.03	32.05
18:00	30.98	30.88	31.01	31.16	31.17
19:00	30.06	29.95	30.15	30.26	30.26
20:00	29.54	29.41	29.63	29.70	29.70
21:00	29.15	29.00	29.23	29.29	29.29
22:00	28.83	28.68	28.92	28.97	28.96
23:00	28.54	28.39	28.62	28.66	28.66
0:00	27.89	27.73	27.98	28.01	28.01
1:00	27.56	27.39	27.65	27.68	27.67
2:00	27.28	27.11	27.36	27.39	27.38
3:00	27.04	26.87	27.12	27.15	27.14
4:00	26.84	26.66	26.92	26.94	26.93
5:00	26.62	26.44	26.70	26.72	26.72
6:00	26.47	26.28	26.55	26.56	26.56
7:00	26.65	26.46	26.73	26.74	26.74

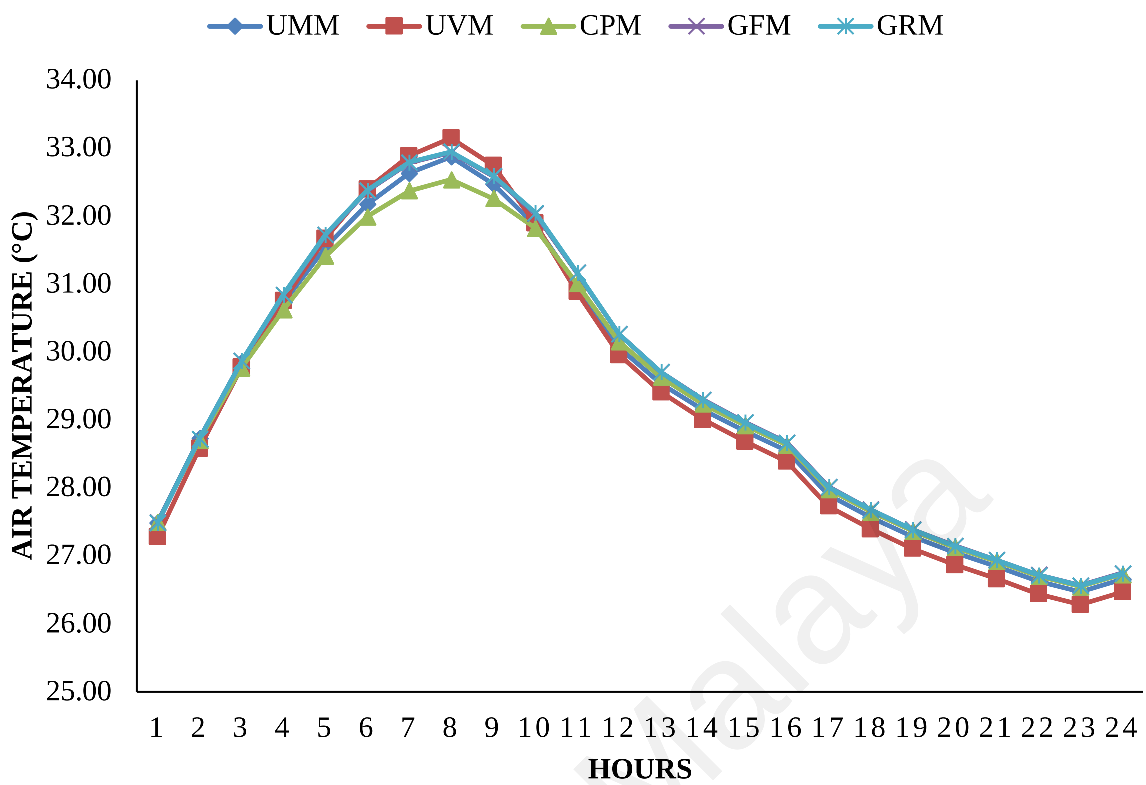


Figure 4.31: The comparison of urban heat mitigation measures on air temperature

A one-way repeated measures ANOVA was conducted to compare readings on the simulated Ta for default UMM (before the UHI mitigation approaches) with UVM, CPM, GFM and GRM. The means and standard deviations are presented in Table 4.57.

Table 4.57: Mean and standard deviation of simulated air temperature for urban heat island mitigation analysis

UHI mitigation measures	n	Mean	Std. Deviation
Default UMM	24	29.32	2.15
UVM	24	29.27	2.30
CPM	24	29.31	2.05
GFM	24	29.44	2.17
GRM	24	29.44	2.18

There was a significant effect for all UHI mitigation measures, Wilks' Lambda = 0.018, $F(4, 20) = 273.84$, $p<0.001$, multivariate partial eta squared = 0.982. In further analysis, a pairwise comparison for the mean of simulated Ta is conducted and summarized in Table 4.58.

Table 4.58: Pairwise comparisons of mean simulated air temperature for urban heat island mitigation approaches

Ta (I)	Ta (J)	Δ Ta (I-J)	Std. Error
UMM	UVM	0.058	0.033
	CPM	0.009	0.026
	GFM	-0.117*	0.011
	GRM	-0.117*	0.011

* The mean difference is significant at the 0.05 level

Ta is important indicators especially when it comes to UHI studies. According to Table 4.58, the UVM was found to have the most influence on ameliorating the Ta in the study area as compared to the other models. However, the improvements were found to be minimal with a reduction of daily average Ta of 0.05°C in the study area. The findings from the current study resemble the findings from a study conducted in Hong Kong by Cheung & Jim (2019), where a 10% increase in tree cover and shrub cover within a 20 m radius led to a reduction of 0.052°C and 0.041°C in Ta, respectively (Cheung & Jim, 2019). On the other hand, the CPM was only capable of reducing the daily average Ta by 0.01°C. Interestingly, both the simulation model of GFM and GRM showed a hotter urban thermal environment as compared to the default UMM despite the introduction of greeneries into the study area.

It was found that the vegetation density of the canopy layer can effectively moderate and reduce environmental temperature (Ibrahim et al., 2014; Ng et. al, 2012). On top of that, Ibrahim et al. (2014) also highlighted green areas with dense vegetation cover performs better in reducing UHII as compared to wide grassland because grass would dry up rapidly under intense sun radiation (Sani, 1986). This could be the reason for the UVM showing better temperature reduction as compared to GFM and GRM. In a study to mitigate UHI effect in the urban areas of Hong Kong, the extensive green roof and intensive green roof were able to reduce the surrounding Ta by 0.4–0.7°C and 0.5–1.7°C, respectively (Peng & Jim, 2013). In another study conducted in Tokyo, implementing roof greening which accounts for an increase in vegetation-covered area by 3.4% and 16.4% resulted in a reduction of maximum surface temperatures by 0.1°C and 0.6°C, respectively (Kinouchi & Yoshitani, 2001). Interestingly, the simulation of GRM in this study showed otherwise, i.e., the introduction of the green roof which made 21.6% of the vegetation-covered area in the urban hotspot resulted with an increase in 0.1°C. Many studies had shown that different types of vegetation could give different thermal reduction properties on the surface temperature of a green roof (Asmat et al., 2008; Niachou et al., 2001).

Various vegetation parameters such as foliage density, plant height, flowering period and the type of soil needed would influence the thermal reduction potential of the vegetation (Spala et al., 2008; Theodosiou, 2003). Besides that, different aspects of a growing media can also influence the performance of a green roof. The medium or substrates chosen for a green roof should be evaluated by organic content, pH, nutrient levels, weight, porosity and water retention capacity (Snodgrass & Snodgrass, 2006). However, more studies are needed to understand the complex interaction between vegetation, surface and building towards the urban microclimate. The influence of the various case scenario on the RH is discussed in the next sub-section.

4.6.4.2 Relative humidity

The hourly RH simulated from each model is presented in Table 4.59 while the variation of RH against time is plotted and shown in Figure 4.32.

Table 4.59: Comparison of simulated relative humidity according to case scenarios

	Relative humidity (%)				
Time	**UMM**	**UVM**	**CPM**	**GFM**	**GRM**
8:00	73.95	74.90	73.90	73.90	73.93
9:00	68.14	69.25	68.20	68.14	68.13
10:00	62.75	63.77	62.96	62.62	62.61
11:00	58.72	59.49	58.99	58.31	58.29
12:00	55.39	55.86	55.75	54.82	54.80
13:00	53.09	53.27	53.59	52.51	52.48
14:00	51.64	51.67	52.35	51.20	51.17
15:00	51.27	51.21	52.20	51.08	51.05
16:00	52.09	52.09	52.68	51.77	51.75
17:00	55.08	55.74	55.17	54.55	54.50
18:00	58.64	59.52	58.53	58.03	58.01
19:00	62.80	63.33	62.49	62.12	62.11
20:00	65.38	65.93	65.05	64.77	64.78
21:00	67.43	68.05	67.10	66.88	66.89
22:00	69.05	69.71	68.72	68.54	68.56
23:00	70.32	71.01	69.99	69.84	69.86
0:00	73.99	74.75	73.62	73.48	73.50
1:00	75.40	76.20	75.03	74.91	74.93
2:00	76.34	77.16	75.97	75.86	75.88
3:00	77.15	78.00	76.79	76.70	76.72
4:00	77.87	78.74	77.52	77.43	77.45
5:00	78.55	79.44	78.20	78.12	78.14
6:00	78.79	79.69	78.44	78.36	78.39
7:00	77.94	78.84	77.62	77.56	77.58

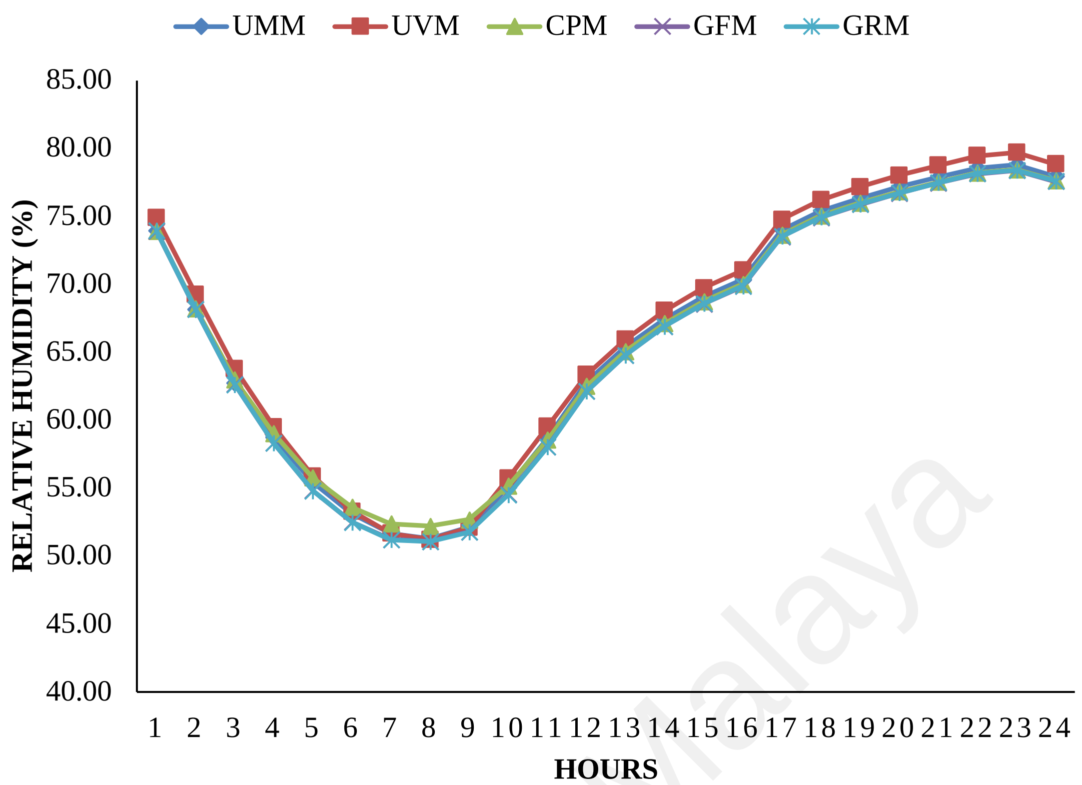


Figure 4.32: The comparison of urban heat mitigation measures with relative humidity

A one-way repeated measures ANOVA was conducted to compare readings on the simulated RH for default UMM (before the UHI mitigation approaches), UVM, CPM, GFM and GRM. The means and standard deviations are presented in Table 4.60.

Table 4.60: Mean and standard deviation of simulated relative humidity for urban heat island mitigation analysis

UHI mitigation measures	n	Mean	Std. Deviation
Default UMM	24	66.32	9.84
UVM	24	66.98	10.08
CPM	24	66.29	9.50
GFM	24	65.90	9.85
GRM	24	65.90	9.87

There was a significant effect for all UHI mitigation measures, Wilks' Lambda = 0.012, F (4, 20) = 397.60, p<0.001, multivariate partial eta squared = 0.988. In further analysis, a pairwise comparison for the mean of simulated RH is conducted and summarized in Table 4.61.

Table 4.61: Pairwise comparisons of mean simulated relative humidity for urban heat island mitigation approaches

RH (I)	RH (J)	Δ RH (I-J)	Std. Error
UMM	UVM	-0.660*	0.066
	CPM	0.038	0.082
	GFM	0.428*	0.036
	GRM	0.427*	0.036

* The mean difference is significant at the 0.05 level

According to Table 4.61, the UVM was found to have the most prominent effect on improving the RH in the study area. The UVM provides a compensating trend on temperature effect where colder areas are found to be higher in RH. Besides the humidity in the air, the main source of humidity in an urban area is mainly from vegetation. The UVM which replaced the concrete pavement with vegetation effectively increased the RH in the urban air. Although vehicles which release water vapour from engine combustion also contributed to urban humidity (Ambrosini et al., 2014). However, the influence of water vapour released from cars can be neglected in this study because the open space in the urban hotspot is a car-free zone. On a side note, although both the GFM and GRM involves the addition of greeneries to the building walls and roofs in the respective models, the effect towards the surrounding RH were minimal. The influence of the various case scenario on the WS is discussed in the next sub-section.

4.6.4.3 Wind speed

The hourly WS simulated from each model is presented in Table 4.62 while the variation of WS against time is plotted and shown in Figure 4.33.

Table 4.62: Comparison of simulated wind speed according to case scenarios

	Wind speed (m/s)				
Time	**UMM**	**UVM**	**CPM**	**GFM**	**GRM**
8:00	1.74	1.08	1.74	1.74	1.77
9:00	1.75	1.07	1.75	1.75	1.77
10:00	1.74	1.06	1.75	1.75	1.77
11:00	1.75	1.06	1.75	1.75	1.77
12:00	1.76	1.06	1.77	1.76	1.79
13:00	1.77	1.06	1.78	1.77	1.79
14:00	1.77	1.06	1.78	1.78	1.80
15:00	1.78	1.06	1.78	1.78	1.80
16:00	1.78	1.06	1.78	1.78	1.80
17:00	1.78	1.05	1.79	1.78	1.80
18:00	1.78	1.05	1.79	1.78	1.81
19:00	1.79	1.05	1.79	1.79	1.81
20:00	1.79	1.05	1.80	1.80	1.82
21:00	1.81	1.05	1.81	1.80	1.83
22:00	1.82	1.05	1.82	1.82	1.84
23:00	1.83	1.06	1.83	1.83	1.85
0:00	1.84	1.06	1.84	1.83	1.86
1:00	1.84	1.06	1.84	1.84	1.87
2:00	1.85	1.05	1.85	1.84	1.87
3:00	1.85	1.05	1.85	1.85	1.87
4:00	1.86	1.04	1.85	1.85	1.88
5:00	1.86	1.04	1.85	1.85	1.88
6:00	1.86	1.03	1.85	1.85	1.88
7:00	1.86	1.03	1.85	1.85	1.88

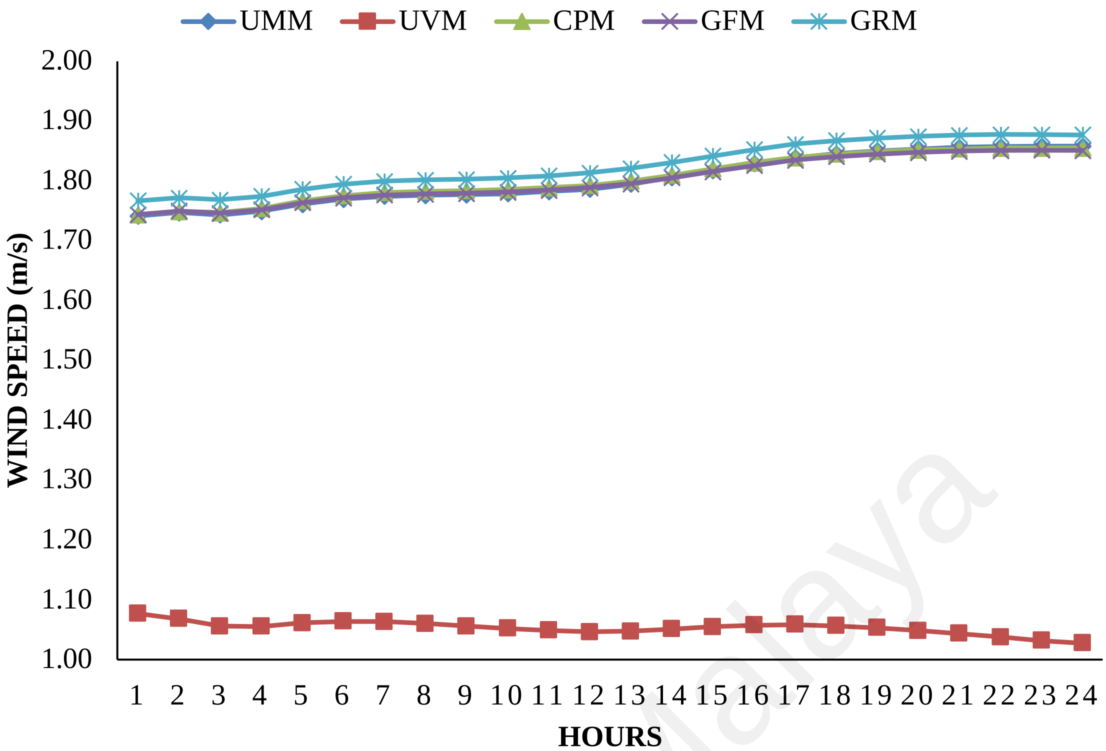


Figure 4.33: The comparison of urban heat mitigation measures on wind speed

A one-way repeated measures ANOVA was conducted to compare readings on the simulated wind speed for default UMM (before the UHI mitigation approaches), UVM, CPM, GFM and GRM. The means and standard deviations are presented in Table 4.63.

Table 4.63: Mean and standard deviation of simulated wind speed for urban heat island mitigation analysis

UHI mitigation measures	n	Mean	Std. Deviation
Default UMM	24	1.80	0.04
UVM	24	1.05	0.01
CPM	24	1.80	0.04
GFM	24	1.80	0.04
GRM	24	1.83	0.04

There was a significant effect for all UHI mitigation measures, Wilks' Lambda = 0.002, F (4, 20) = 2557.51, p<0.001, multivariate partial eta squared = 0.998. In further analysis, a pairwise comparison for the mean of simulated WS is conducted and summarized in Table 4.64.

Table 4.64: Pairwise comparisons of mean simulated wind speed for urban heat island mitigation approaches

WS (I)	WS (J)	Δ WS (I-J)	Std. Error
UMM	UVM	0.749*	0.010
	CPM	-0.001	0.001
	GFM	0.002	0.001
	GRM	-0.023*	0.001

* The mean difference is significant at the 0.05 level

WS has an important role to facilitating the convective heat exchange between the urban atmosphere, vegetation, buildings and people. In urban planning for high-density cities, allowing constant air ventilation especially in the streets will benefit these dense urban areas (Ng, 2009). This is because high WS facilitates the air mixing in urban areas preventing heat stagnation points which latter contributes to the formation of UHI. According to Table 4.64, the GRM was found to be the most effective in improving the WS in the study area as compared to the other models. However, it was important to note that the improvements were small and even negligible as shown in the daily average of 1.83 m/s as compared to 1.80 m/s in the default UMM. Both CPM and GFM did not affect the WS variation in the study area. In contrast, the UVM was found to drastically reduce the daily average WS to 1.05 m/s. The reduction may be attributed to the trees introduced to the study area. The existence of barrier increases surfaces roughness and the height of anemometric boundary layer which would create an air preferential direction which induces high WS gradient in narrow spaces (Ambrosini et al., 2014). In simpler terms, the additional trees would obstruct wind flow near the surface level which results in a more stagnant wind environment. Besides, replacing the concrete pavement in the open space of the default UMM with grasses may lower wind speed due to the increase in surface roughness. Due to the complexity of microclimate variations within the urban setting, future studies could optimise the synergetic effect of urban greenery and wind on urban cooling in high-density urban areas (Tan et al., 2016). In the next sub-section, the influence of the various case scenario on the Tmrt is discussed.

4.6.4.4 Mean radiant temperature

The hourly Tmrt simulated from each model is presented in Table 4.65 while the variation of Tmrt against time is plotted and shown in Figure 4.34.

Table 4.65: Comparison of simulated mean radiant temperature according to case scenarios

	Mean radiant temperature (°C)				
Time	UMM	UVM	CPM	GFM	GRM
8:00	18.92	22.90	18.97	18.95	23.03
9:00	48.39	35.41	49.63	49.08	49.16
10:00	65.21	50.34	67.50	66.55	66.62
11:00	67.09	55.08	70.35	69.01	69.04
12:00	66.50	58.97	70.52	68.83	68.79
13:00	66.17	55.20	70.57	68.65	68.53
14:00	69.53	58.25	73.26	71.57	71.45
15:00	74.18	66.42	76.87	75.64	75.58
16:00	58.87	63.64	60.81	59.99	60.00
17:00	45.23	40.83	46.41	46.04	46.13
18:00	35.87	33.57	36.54	36.46	36.56
19:00	23.82	24.79	24.16	24.31	24.32
20:00	21.99	23.47	22.29	22.44	22.42
21:00	21.08	22.74	21.39	21.51	21.48
22:00	20.47	22.23	20.78	20.88	20.85
23:00	19.98	21.81	20.28	20.37	20.34
0:00	19.17	21.08	19.47	19.55	19.52
1:00	18.71	20.65	19.01	19.07	19.04
2:00	18.31	20.29	18.61	18.67	18.64
3:00	17.99	19.99	18.28	18.34	18.31
4:00	17.72	19.74	18.00	18.06	18.03
5:00	17.44	19.48	17.72	17.77	17.74
6:00	17.23	19.29	17.51	17.55	17.52
7:00	17.36	19.40	17.63	17.67	17.64

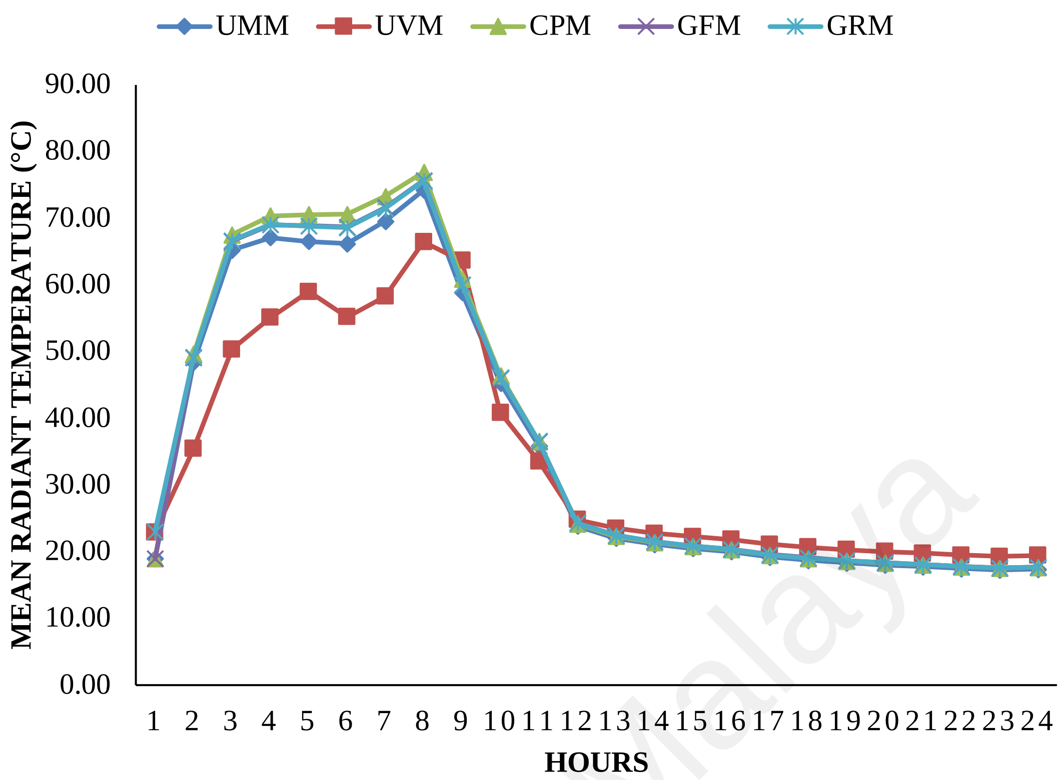


Figure 4.34: The comparison of urban heat mitigation measures on mean radiant temperature

A one-way repeated measures ANOVA was conducted to compare readings on the simulated Tmrt for default UMM (before the UHI mitigation approaches), UVM, CPM, GFM and GRM. The means and standard deviations are presented in Table 4.66.

Table 4.66: Mean and standard deviation of simulated mean radiant temperature for urban heat island mitigation analysis

UHI mitigation measures	n	Mean	Std. Deviation
Default UMM	24	36.13	21.83
UVM	24	33.98	17.01
CPM	24	37.36	23.13
GFM	24	36.96	22.48
GRM	24	37.11	22.35

There was a significant effect for all UHI mitigation measures, Wilks' Lambda = 0.066, F (4, 20) = 70.32, p<0.001, multivariate partial eta squared = 0.934. In further analysis, a pairwise comparison for the mean of simulated Tmrt is conducted and summarized in Table 4.67.

Table 4.67: Pairwise comparisons of mean simulated mean radiant temperature for urban heat island mitigation approaches

Tmrt (I)	Tmrt (J)	Δ Tmrt (I-J)	Std. Error
UMM	UVM	2.153	1.273
	CPM	-1.222*	0.285
	GFM	-0.822*	0.146
	GRM	-0.980*	0.195

* The mean difference is significant at the 0.05 level

Tmrt is an important indicator to determine a person's OTC level as it represents the summation of all short-wave and long-wave radiation fluxes on a person. According to Table 4.67, the UVM is identified as the most effective model to improve the Tmrt in the urban hotspot. This reduction in average daily Tmrt can be associated with the introduction of trees and grasses through the UVM in the study area. Trees which provides shading are an effective mechanism in reducing direct SR while grasses which enhance evapotranspiration in the study area would be effective in reducing near-surface temperature. Together, the UVM substantially contribute to the betterment of the Tmrt. There is no competition at all from the remaining case scenarios. Although the GFM and GRM both introduces greeneries into the study area, the shading effect which is provided by the trees is the determining factor in improving localized Tmrt. From several studies, solar radiation was found to have the most significant influence on OTC level at outdoor spaces in a tropical climate (Bakar & Gadi, 2016; Qaid et al., 2016; Yang et al., 2013).

As such, providing shades with trees as done in the UVM model is deemed beneficial for the people to adapt to the outdoor thermal environment. On a side note, the provision of artificial shade in future urban planning practices could also improve the thermal environment within an urban area (Lee et al., 2020). In the next sub-section, the influence of the various case scenario on PET is discussed.

4.6.4.5 Physiological Equivalent Temperature (PET)

The simulated microclimate data from each model is also used to evaluate PET in the study area. The hourly PET simulated from each model is presented in Table 4.68 while the variation of PET against time is plotted and shown in Figure 4.35.

Table 4.68: Comparison of simulated Physiological Equivalent Temperature according to case scenarios

	Physiological Equivalent Temperature (PET) (°C)				
Time	UMM	UVM	CPM	GFM	GRM
8:00	22.10	23.60	22.20	22.20	23.20
9:00	34.70	29.70	35.30	35.10	34.90
10:00	44.60	38.10	45.90	45.50	45.30
11:00	46.60	41.60	48.20	47.60	47.60
12:00	46.90	44.50	49.10	48.40	48.40
13:00	47.50	43.00	49.70	49.00	49.00
14:00	49.80	45.10	51.70	51.10	51.10
15:00	52.80	49.90	53.90	53.60	53.60
16:00	43.90	48.00	44.70	44.60	44.60
17:00	36.50	35.30	36.90	37.00	37.00
18:00	31.30	31.20	31.60	31.80	31.80
19:00	25.50	26.50	25.60	25.90	25.90
20:00	24.50	25.40	24.70	24.80	24.80
21:00	23.90	24.80	24.10	24.20	24.20
22:00	23.60	24.40	23.70	23.80	23.80
23:00	23.20	24.00	23.30	23.40	23.40
0:00	22.50	23.30	22.70	22.70	22.60
1:00	22.10	23.00	22.20	22.30	22.30
2:00	21.80	22.60	22.00	22.00	21.90
3:00	21.40	22.50	21.60	21.60	21.60
4:00	21.20	22.20	21.30	21.40	21.30
5:00	21.00	22.00	21.10	21.10	21.10
6:00	20.80	21.80	20.90	21.00	21.00
7:00	21.00	22.00	21.10	21.10	21.10

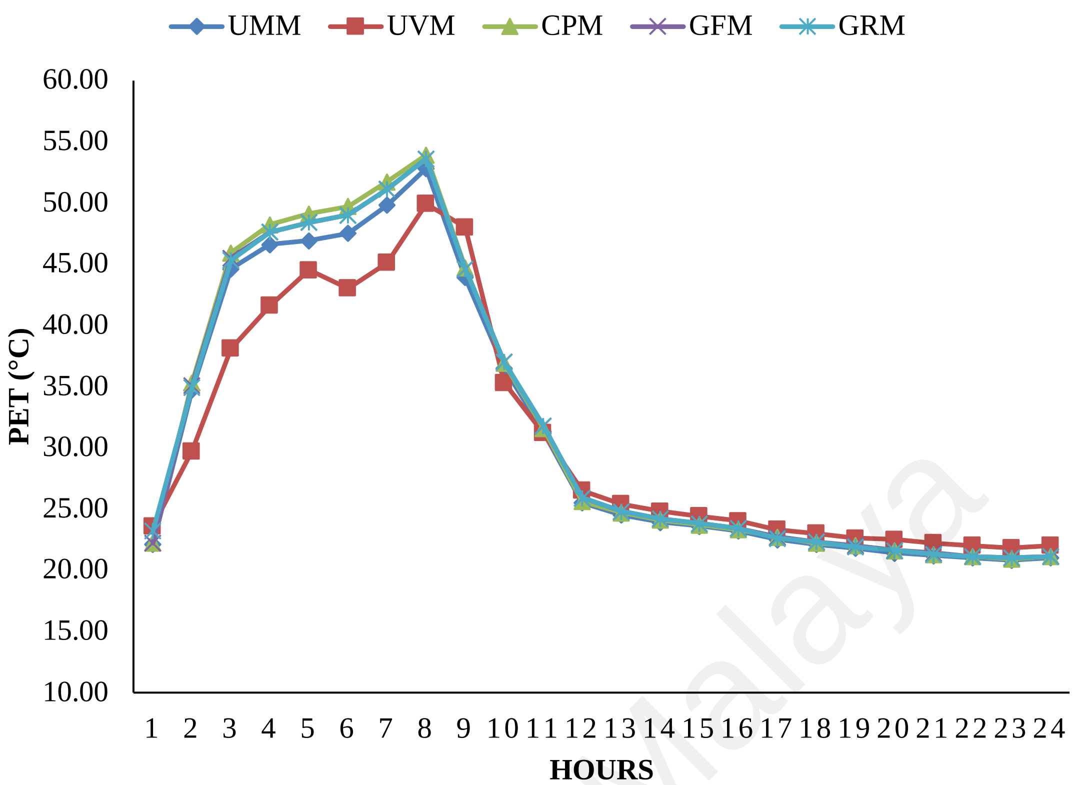


Figure 4.35: The comparison of urban heat mitigation measures on Physiological Equivalent Temperature

A one-way repeated measures ANOVA was conducted to compare readings on the simulated PET for default UMM (before the UHI mitigation approaches), UVM, CPM, GFM and GRM. The means and standard deviations are presented in Table 4.69.

Table 4.69: Mean and standard deviation of simulated Physiological Equivalent Temperature for urban heat island mitigation analysis

UHI mitigation measures	n	Mean	Std. Deviation
Default UMM	24	31.22	11.49
UVM	24	30.60	9.73
CPM	24	31.81	12.14
GFM	24	31.72	11.89
GRM	24	31.73	11.86

There was a significant effect for all UHI mitigation measures, Wilks' Lambda = 0.208, F (4, 20) = 19.02, p<0.001, multivariate partial eta squared = 0.792. In further analysis, a pairwise comparison for the mean of simulated PET is conducted and summarized in Table 4.70.

Table 4.70: Pairwise comparisons of mean simulated Physiological Equivalent Temperature for urban heat island mitigation approaches

PET (I)	PET (J)	Δ PET (I-J)	Std. Error
UMM	UVM	0.613	0.557
	CPM	-0.596*	0.146
	GFM	-0.500*	0.090
	GRM	-0.512*	0.094

* The mean difference is significant at the 0.05 level

According to Table 4.70, the UVM is found to be the most effective urban heat mitigation model to reduce the average daily of PET by 0.62°C PET as compared to the existing default UMM. However, despite the reduction in daily average PET to 30.60°C PET, the value is still far from the preferred temperature (22.74°C PET) or neutral temperature (24.17°C PET) of the urban communities in the study area. Besides, the daily average PET value from UVM is also above the temperature to express thermal comfort (25.61°C PET). This indicates that urban communities in the study area would be expected to experience slight thermal discomfort even after the implementation of UVM. Fortunately, the daily average of PET falls well within the acceptable range of temperature at outdoors (28.86 to 34.48°C PET). The recommendation of the best-case scenario on improving the urban microclimate is discussed in the next sub-section.

4.6.5 Recommendation of urban heat mitigation strategies based on simulation result

Based on the findings from section 4.6.4, the most feasible urban heat mitigation measures for the urban hotspot in MJ are discussed in this section.

4.6.5.1 The most effective urban heat mitigation model among the four case scenarios

The findings from various urban heat mitigation pairwise analysis showed that there are pros and cons for implementing each model. The most effective urban heat mitigation model in ameliorating key urban microclimate parameters is summarized in Table 4.71.

Table 4.71: The most effective urban heat mitigation model in ameliorating key urban microclimate parameters

Microclimate parameters	Most effective urban heat mitigation model	Difference	
		Mean	Std. Error
Ta (°C)	UVM	0.058	0.033
RH (%)	UVM	-0.660*	0.066
WS (m/s)	GRM	-0.023*	0.001
Tmrt (°C)	UVM	2.153	1.273
PET (°C PET)	UVM	0.613	0.557

* The mean difference is significant at the 0.05 level

According to Table 4.71, it is obvious that the UVM performs very well in improving urban microclimate parameters such as Ta, RH, Tmrt and PET. The GRM was the other urban heat mitigation model to be capable of improving the WS in the urban hotspot. Wind activity is important to facilitate evaporation (heat transfer from the human body to the environment through sweating mechanism) to improve the OTC levels in a tropical climate. Interestingly, both UVM and GRM are only found to be significantly capable of improving RH and WS, respectively. More studies are needed to identify the reasons behind the insignificance of urban heat mitigation model in improving Ta, Tmrt and PET.

Although urban greening is proven to be effective in ameliorating UHI impact, its capabilities to reduce global warming potential, surface thermal energy flux and building energy usage remain largely unexplored in a tropical city. Future research could be dedicated to unravelling these influences which are not covered in the current study. Besides that, trees of different species and morphological properties are known to have varying cooling potential towards the urban thermal environment (Kong et al., 2017; Morakinyo et al., 2020; Morakinyo et al., 2017; Ouyang et al., 2020). Similarly, more studies are needed to unravel the complexity in urban greening in terms of plant species, orientation, the spatial distribution of vegetation, maintenance and other related issues for effective urban greening implementation. Besides, soil physical and chemical parameters such as soil depth, porosity, shear strength, nutrient availability, pH level and other relevant parameters are equally important to ensure effective urban greening implementation (Chau et al., 2020; Jim, 1998). Despite the limitations in the current study, it can be agreed that urban greening is a promising strategy to be applied in a tropical city to mitigate UHI impact.

In Malaysia, the blueprint which promotes sustainable town planning can be found published in 2012 by PLANMalaysia (Federal Department of Town and Country Planning) on “Guidelines on Green Neighbourhood Planning”. Unlike the master plan for urban design and planning in Singapore, the guidelines by PLANMalaysia serves more as a guiding principle for state governments, local authorities, developers and non-governmental bodies to plan, design and control the development of the green neighbourhood. The guideline is proposed following a few national policies such as the 10th Malaysia Plan, National Physical Plan, National Urbanization Policy, National Climate Change Policy, and so on. Hence, the UVM is considered as a promising urban heat mitigation strategy which is also in line with various national policies and guidelines. The integration of current findings into existing urban policy and guidelines is presented in the next sub-section.

4.6.5.2 Integration of urban heat mitigation findings into urban policy and guidelines

In Malaysia, related policy and guidelines on urban ecosystem management began as early as in the 1980s (Ilyani Ibrahim et al., 2014). In terms of existing legislation, the National Urbanization Policies 1 & 2 (NUP 1 & 2) succinctly elucidated the need to accelerate climate compatible urban developments that play an optimal role as the engine of economic growth without undermining the sustainability of urban communities (PLANMalaysia, 2016). The aforementioned urban policies are supported by National Physical Plans, State Structure Plans, Local Plans, Special Area Plans as well as various guidelines and acts. They guide and coordinate urbanization process with an emphasis of maintaining the balance between social, economic and physical developments within the country. However, none of the urban policies seemed to implicitly address the issues associated with UHI except for several statements in NUP 1 and NUP 2. In NUP 1, the 26th policy addresses developments that minimize UHI impacts as a viable measure to create a conducive liveable urban environment (PLANMalaysia, 2016). On the other hand, NUP 2 elaborates vertical and rooftop gardening as a potential strategy to reduce urban warming impacts in city centres (PLANMalaysia, 2016).

The development of sustainable smart cities is often halted due to a lack of climate knowledge among urban planners (American Planning Association, 2011). Therefore, rapidly developing cities is inevitable to suffer from the deterioration of the urban environment because the association of urban growths to climate change is often overlooked. The complex occurrence of UHI emphasized the importance of interdependency and strong partnership between various stakeholders to ensure effective implementation of urban heat mitigation strategies. As UHI is closely related to the land use/land cover and the environment (particularly on atmospheric conditions), governmental bodies in Malaysia such as Department of Meteorology Malaysia (MetMalaysia) and Department of Environment (DOE) should be actively involved in the environmental monitoring while Federal Department of Town and Country Planning (PLANMalaysia) should be responsible with policy making and implementation (Ibrahim et al., 2014). Besides that, other stakeholders such as state or local authorities, non-governmental organizations, private sectors, research institutes and the public should also participate along through programs such as Local Agenda 21 Kuala Lumpur by Kuala Lumpur City Hall (KLCH).

Unfortunately, these existing policies were only able to address UHI issues on the surface and their implementation is still meagre as shown through existing literature (Ramakreshnan et al., 2019). Even though PLANMalaysia has proposed several guidelines and policies to assist the local authorities in various sustainable urban planning and green neighbourhood initiatives, more evidence is needed to encourage the effective implementation of such guidelines and policies at various level (PLANMalaysia, 2020). Intrinsically, exploring urban heat mitigation strategies through modelling and simulation approaches can provide stakeholders with actual figures to make better-informed decisions. As shown through the findings in the current study, the ENVI-MET is a reliable tool and should be introduced to various urban planners through active social engagement activities and dialogue sessions with stakeholders in the future.

4.6.6 Summary

In summary, the simulation of urban heat mitigation strategy using the ENVI-MET software is proven to be a reliable tool to evaluate the influence of urban design and greening towards the improvement of urban microclimate. As the study of OTC and UHI is inter-related, mitigation measures in UHI can indirectly influence thermal comfort in outdoors too. While urban greenery on land surface is recommended, the urban ecosystem management in tropical cities should also encourage green façade and green roof and use efficiently other shading mechanisms such as covered walkways and pedestrian arcades to improve the local urban microclimate. The implementation of UVM should be carried out wherever possible as it is also in line with various national policies and guidelines. Despite being able to prove the effectiveness of urban greening in ameliorating UHI impact, more research is needed to unravel its capabilities to reduce global warming potential, surface thermal energy flux and even its influence towards building energy usage which is not covered in this study. More studies are also needed to unravel the complexity in urban greening in terms of plant species, orientation, the spatial distribution of vegetation, maintenance and other related issues for effective urban greening implementation.

CHAPTER 5: CONCLUSION

5.1 Introduction

Chapter 5 is allocated to provide an overview of the findings from the research conducted. The highlights from Phases 1, 2 and 3 are presented. Next, the limitations and strengths of the current study are elaborated. Finally, the recommendations for future work are suggested.

5.2 Key findings from Phase 1, 2 and 3

5.2.1 Phase 1: Urban microclimate variations in selected study area

Continuous monitoring of the meteorological variables for Ta, RH, WS and wind direction, and SR is conducted at 2 m height using a customized automated weather station (AWS). The temporal variations in urban microclimate in terms of monthly and daily-diurnal variations are identified. Despite the variations in both Ta and RH, the selected study area experienced typical hot-humid tropical climate with high mean Ta of 30.23°C (SD=3.90°C) and high mean RH of 69.09% (SD=13.75%). Light air activity representing WS of 0.5 to 1.5 m/s is predominant (43.3%) with the average WS recorded at 0.63 m/s (SD=0.57 m/s). Influencing factors such as the existence of high-rise buildings, rough pavement surfaces and other obstructing objects could be the reason for explaining the low WS in the study area. The study area also receives ample SR with an average of 98.21 W/m^2 (SD=119.74 W/m^2) daily. The high variation in SR is mainly attributed to the unpredicted cloud cover in the study area. All four selected meteorological variables from MetMalaysia were weakly correlated with the data sets from AWS. Hence, the AWS placed in the selected study area can evaluate urban heat exposure more accurately as compared to MetMalaysia's principal monitoring station.

5.2.2 Phase 2: The influence of urban heat towards the outdoor thermal comfort level and human health implications in study area

In terms of OTC assessment, the microclimate data from the AWS is used to evaluate the physiological OTC indices while a large-scale questionnaire survey is conducted to evaluate the psychological OTC thermal responses. The questionnaire has also adopted questions to assess heat-related health implications which are further distinguished according to physical, psychosomatic and psychological health symptoms.

5.2.2.1 The outdoor thermal comfort level of urban communities in study area

In summary, an adaptive approach was used to evaluate the OTC level of urban communities in MJ. Among the five selected OTC indices, PET was chosen to represent physiological OTC. In general, the urban communities are expected to experience slight physiological heat stress with an average of 29.45°C PET (SD=2.11°C PET). The findings from physiological OTC indicated that only 37.2% (n=321) reported positive thermal sensation. In further analysis, the findings from physiological OTC was found to contradict with the findings from psychological OTC where 73.8% (n=856) of the respondents reported positive thermal sensation. Results from 1160 eligible respondents also indicated a majority (n=806, 69.5%) wanted a cooler environment despite having 71.4% (n=828) of the respondents expressing thermal acceptance. Lastly, it was found that only 44.8% (n=520) of the urban communities were at thermal comfort level while the others expressed thermal discomfort. Respondents in this study were found to exhibit traits of adaptive thermal comfort when they perceived the environment to be better as compared to measured microclimate conditions.

The association of OTC with selected sociodemographic variables revealed ethnicity (p=0.002) to be significantly associated with expressing thermal response while gender (p=0.670), age group (p=0.113) and duration spent outdoors in a day (p=0.814) were not significantly associated. In terms of diurnal variation in OTC, the preference towards a cooler environment was found to sustain from 8.00 am to 8.00 pm despite a change in MTSV at 7.00 pm. The MTPV which remained positive shows that the respondents were expecting a cooler environment even after sunset. In terms of thermal comfort level, the MTCV is influenced to a certain extent by the variation in SR.

By expressing psychological OTC via PET, it was found that the urban community expresses neutral thermal sensation at 24.17°C PET, while the acceptable range of temperature for at least 70% of the population in the study area is 28.86 to 34.48°C PET. The preferred temperature of the urban community is 22.74°C PET. Meanwhile, the temperature for an individual to express thermal comfort/discomfort is 25.61°C PET. Based on these findings, heat stress guideline is proposed for a tropical city. The proposed heat stress guideline has two advantages. Firstly, it is easily evaluated through open-source software (RayMan Pro) with commonly found meteorological parameters. Secondly, it is expressed in a commonly known unit (°C PET) that could be easily understood by any layperson. In future, more effort and studies are needed to promote and identify its practicability among other relevant stakeholders.

5.2.2.2 The impact of urban heat on human health implications

Human health complications that arise due to urban heat is explored in this study. In general, a majority of the urban community were found to have low severity of physical health impact (n=819, 74.2%), psychosomatic health impact (n=693, 65.9%), anxiety (n=931, 84.6%) and depression (n=799, 73.0%).

Heat exhaustion was found to be the most reported physical symptom with about half (n=569, 49.2%) of the respondents reported of experiencing it. Tiredness was found to be the most reported psychosomatic symptom with 77.0% (n=891) of the respondents reported experiencing it. Besides, psychosomatic symptoms such as trouble sleeping (n=769, 66.5%) and headache (n=684, 59.1%) were also experienced by more than half of the respondents. In terms of anxiety-related psychological health symptoms, commonly reported symptoms are feeling nervous (n=518, 44.8%), trouble relaxing (n=509, 44.0%) and being easily annoyed (n=471, 40.7%). Meanwhile, commonly reported depression-related psychological health symptoms are feeling tired (n=872, 75.4%), little interest in doing things (n=717, 62.0%), poor appetite or overeating (n=715, 61.8%), trouble falling or staying asleep (n=708, 61.2%) and trouble with concentrating at home, school, work or while doing other things (n=674, 58.3%).

Through EFA, physical health is clustered into two health components which are sensory organ pain (5 items) and heat-related illnesses (4 items) while psychosomatic health is clustered into three health components which are cardiopulmonary (6 items), pain (5 items) and fatigue (2 items) related symptoms. In terms of psychological health, the three health components identified were anxiety (7 items), somatization (5 items) and depression (4 items) related symptoms. The urban heat significantly affected pain-related psychosomatic symptoms (p=0.016), as well as psychological health in terms of anxiety (p=0.022) and somatization (p=0.041) related symptoms. Other health components were found to be not significantly associated with urban heat.

It was also found that confounding factors such as gender, age group, ethnicity and duration of exposure at outdoors in a day have varying influence towards the health outcomes. More studies are needed to unravel the influence of these confounding factors besides conducting subject-specific studies involving vulnerable and sensitive population. Future research direction should also consider conducting longitudinal studies which may be beneficial in unravelling the long-term impact of urban heat exposure towards the health and well-being of urban communities in a tropical city.

Lastly, respondents were asked if the outdoor thermal discomfort should be considered as a public health issue. A majority agreed that the outdoor thermal discomfort would have an impact on human health (n=907, 78.4%) and should be addressed as a public health issue (n=862, 75.0%).

5.2.3 Phase 3: Exploring urban heat mitigation measures in a tropical city via modelling and simulation approach

In Phase 3, the urban heat mitigation measures in a tropical city are explored via a modelling and simulation approach. The selected study area was developed in ENVI-MET and validated to provide accurate and reliable microclimate simulation data. Then, four UHI mitigation measures which emphasize on urban design and greening is simulated and compared to identify the best measures in improving the urban microclimate.

5.2.3.1 The development and validation of urban microclimate model for modelling and simulation

The UMM representing the selected study area was developed through ENVI-MET and validated with two sets of data representing yearly and daily average meteorological data. The simulation of the urban microclimate variation was conducted for 24 hours with simple radiative forcing applied for Ta and RH. The UMM was found to be more accurate and reliable to simulate monthly average as compared to daily average microclimate variations. It was observed that ENVI-MET dealt with stable monthly average meteorological variations much better as compared to day-to-day dynamic-complex instantaneous variations. The weak association for daily average microclimate simulation is postulated to be influenced by the complex micro-interaction between the built and natural environment. More studies are needed to provide the necessary scientific evidence which is lacking in the current study.

5.2.3.2 Simulating urban heat mitigation measures for the improvement of urban microclimate

Four UHI mitigation measures to improve the urban microclimate were explored. Urban hotspots are identified as areas which are found to have a slower heat dissipation rate as compared to the other simulated regions in the UMM. Four sets of model geometry were customised according to the respective case scenarios which are Cool Pavement Model (CPM), Urban Vegetation Model (UVM), Green Façade Model (GFM) and Green Roof Model (GRM). The findings from various urban heat mitigation pairwise analysis showed that there are pros and cons for implementing each model. The UVM performs very well in improving urban microclimate parameters such as Ta, RH, Tmrt and PET. From several studies, SR was found to have the most significant influence on OTC level at outdoor spaces in a tropical climate. As such, providing shades with trees as done in the UVM model is deemed beneficial for the people to adapt to the outdoor thermal environment. The GRM was the other urban heat mitigation model to be capable of improving the WS in the urban hotspot. Wind activity is important to facilitate evaporation to improve the OTC levels in a tropical climate. Interestingly, both UVM and GRM are only found to be significantly capable of improving RH and WS, respectively.

More studies are needed to identify the reasons behind the insignificance of urban heat mitigation model in improving Ta, Tmrt and PET.

The UMM simulation using the ENVI-MET software is proven to be a reliable tool to evaluate the influence of urban design and greening towards the improvement of urban microclimate. As the study of OTC and UHI is inter-related, mitigation measures of UHI can indirectly influence local OTC level too. Although the findings from this research have been able to shed some light into several ways to mitigate UHI phenomenon at the microscale, there is much to be done in terms of urban ecosystem management in a rapidly developing tropical city. Besides urban greening, future studies should also explore other urban design approach and effective sustainable cooling measures to improve the urban microclimate and local OTC level.

5.3 Limitations of current research

There were a few shortcomings identified throughout the conduct of the research study. As such, the limitation of the current research is collectively presented in this sub-section.

5.3.1 The limitations in continuous urban microclimate observation through point measurements

The continuous monitoring of the microclimate variations in the study area was conducted through a point measurement in the centre of the selected study area due to the financial constraint of the research project. Although the monitoring coverage in this study followed the standard urban microclimate observation guidelines, the meteorological variations may fluctuate as they move further away from the measuring point. This variation is most noticeable for highly varying parameters such as wind speed and solar radiation. As such, the use of more than one AWS would be able to provide more precise monitoring of the microclimate variations. Also, if the AWS are arranged in a gridded network, the microclimate data may even be interpolated or extrapolated to provide more extensive monitoring of the urban climate as compared to the existing approach.

5.3.2 The influence of thermal adaptive behaviour in distorting the true outdoor thermal comfort level

As shown by this study, any OTC research could not be conducted by either physiological and psychological approach alone due to the complexity of what the mind perceives as opposed to how the body feels. Although control measures were taken to reduce the influence of thermal adaptation in this study, the contradicting findings of physiological OTC with psychological OTC are evidence that there are more to be explored in terms of thermal adaptation. In this study, a combination of physiological and psychological approach has been undertaken to unravel the true OTC level of the urban community in the study area. However, due to the nature of the current study, the thermal adaptation features could not be further explored.

5.3.3 The limitation of self-reported health questionnaire in identifying human health implications due to urban heat exposure

In identifying the human health implications from urban heat exposure, the current research has adopted a cross-sectional approach to assess physical, psychosomatic and psychological health symptoms that arise through an expert validated self-reported health questionnaire. There are mainly two limitations to this approach. Firstly, the cross-sectional approach is known to induce constraints on the exploration of causality between the variables being assessed. Although urban heat exposure and health outcomes were assessed simultaneously, it is difficult to determine if thermal discomfort led to the occurrence of health symptoms or vice versa. Nonetheless, the findings from this study were able to serve as an exploratory initiative in unravelling some of the most commonly reported physical, psychosomatic and psychological health symptoms because of urban heat exposure. In the future study, a longitudinal study could be carried out to understand the causal inference between urban heat and the health outcomes in a tropical city.

Secondly, the limitation lies in the self-reported health questionnaire. In many circumstances, the response from the urban community could be biased because of under-reporting or over-reporting which may affect the outcome of the research. In this research, the sample size was increased to minimize the biases in identifying a particular health outcome because of urban heat exposure. Besides that, the survey session is carefully carried out in an individual face-to-face approach to ensure that the health symptoms reported by the respondents were solely related to urban heat exposure. Despite the approach undertaken, future studies could carry out in-depth analyses involving medical practitioners who have a better knowledge of diagnosing health outcomes.

5.3.4 Limitations in urban microclimate modelling and simulation

In exploring various urban heat mitigation measures, a UMM of the selected study area was developed and validated to be reliable in reproducing relatively accurate microclimate variations, as compared to the observed meteorological variation from continuous monitoring in the study area. However, the modelling and simulation work in the ENVI-MET software was restricted to a model with a 200 x 200 x 25 (x-y-z) grid because the access to the unlimited model size would require the purchase of a license which is about RM5000 (990 EUR) per year. Moreover, a top performance laptop preferably with a 16 GB of RAM is needed to smoothly run the software. The laptop used in the research which could only support an upgrade up to 8 GB of RAM struggles especially during the simulation of microclimate variations in the UMM. A full 24-hour microclimate simulation would require an average of 2-3 days of computation. Often, the software crashes and the whole process of simulation needs to be repeated all over again. Due to the limitations in both hardware and software in the current research, future studies could be conducted using the licensed version of the software with a more powerful computer to simulate a larger study area which could not be accomplished in this study.

5.4 Strength of the study

The completed study has contributed significantly to knowledge advancement in UHI research in a tropical city. There are four strengths of the study. Firstly, the continuous monitoring approach in this study was more reliable in recording near-surface urban microclimatic variations. This study showed that the existing principal monitoring station of MetMalaysia was incapable to accurately describe the meteorological variations especially in the city centre of KL due to the complex interaction between the natural-environment and built-environment. Hence, the AWS placed in the study area can better record the formation of UHI and this monitoring approach should be adopted by local authorities to ensure there is a proper track record for detailed UHI research in future.

Secondly, this study is among the first extensive OTC research conducted in the city centre of KL which considers both physiological and psychological OTC assessment approach. This approach was able to find coherence between the state of mind and body experiencing thermal stress and subsequently unravel the true OTC level of the urban community. This approach is proven to be more reliable as compared to only assessing either the physiological or psychological OTC alone.

Thirdly, this study provided a research direction on how physical, psychosomatic and psychological health symptoms can be associated with being thermally discomfort in an urban outdoor area. A total of 1160 respondents were involved in the large-scale questionnaire to identify commonly reported physical, psychosomatic and psychological health symptoms which are related to urban heat exposure. The findings from this study can serve as a baseline study to identify human health implications from urban heat exposure and be referred to when designing a longitudinal study in future.

Lastly, this study explored several UHI mitigation measures on urban design and greening to improve the urban microclimate through a 3D modelling and simulation approach. The ENVI-MET software used for the urban microclimate simulation was found to be a reliable and efficient tool for UHI mitigation studies. Furthermore, this study which serves more as an initial exploratory study has shown that there are more strategies to be experimented to mitigate the urban heat from a tropical city.

5.5 Recommendations for future work

5.5.1 Developing an extensive microclimate monitoring system

The lack of a continuous microclimate monitoring system prevents a thorough understanding of the UHI phenomenon in a tropical city. Often, the lack of an advance and extensive monitoring system is attributed to the lack of funds allocated as these monitoring devices are not cheap. Also, the maintenance cost could be burdensome to local or state governments. Besides that, the current mobile traverse monitoring method is restricted in terms of providing a synchronized observation despite offering high spatial coverage. Hence, future studies should be dedicated to inventing cheap but reliable integrated sensors to be used extensively for the monitoring of microclimate variations. This extensive monitoring network may contribute to the fundamental development of an early warning system which can produce heat maps for the effective communication of extreme weather events that might occur soon.

5.5.2 Exploring the temporal influence of monsoon seasons on urban heat island and outdoor thermal comfort conditions

The influence of monsoonal season on UHI and OTC level in the study area could not be neglected entirely despite having hot-humid climate throughout the year. There is the possible influence of the Northeast monsoon (November to March), Southwest monsoon

(June to September) and the two inter-monsoon periods on the variations of microclimate parameters in the study area. As identified through relevant literature, seasonal monsoon is believed to have a direct influence on the wind movement which is important to ameliorate the urban heat in a city and for the forecasting of local OTC level. Future studies could be dedicated to identifying the significance of the difference in UHI intensity and the OTC level across the different monsoon seasons.

5.5.3 Bridging the research gap in outdoor thermal comfort research

5.5.3.1 Adaptive thermal comfort

The influence of thermal adaptation plays a major role in misleading the real OTC conditions of a person. As was emphasized in the current study, the factors influencing thermal adaptation are yet to be fully understood in OTC research. Such in-depth knowledge on the subject matter would require future research to be conducted using a more sophisticated approach combining both qualitative and quantitative measures.

5.5.3.2 Sociodemographic factors influencing individual outdoor thermal comfort level

The prevalence of OTC conditions is affected by various reasons. In this study, only a few sociodemographic parameters such as ethnicity, gender, age and duration spent outdoors in a day were tested to identify their influence towards the reported OTC conditions. More studies are needed to identify the influence of other sociodemographic factors on the OTC level especially those factors which are not covered in this study. Unravelling the relationship between these factors is important to better understand the OTC conditions and how people are adapting to the changing climate.

5.5.4 A heat stress guideline for tropical cities in South East Asia

The occurrence of thermal discomfort is one of the important findings in OTC studies because prolonged outdoor heat exposures would impact the well-being of urban communities which then leads to thermal heat stress and other heat-related illnesses. As there are no established heat stress indicators for the tropical cities in South East Asia, heat stress guideline has been proposed through this study. However, more research should be conducted to investigate the feasibility of the proposed guideline for the application in tropical cities in South East Asia.

5.5.5 Human health implications from urban heat exposure with diagnosis from medical practitioners

The current study sheds light into the prevalence of physical, psychosomatic and psychological health symptoms which arises due to urban heat exposure. However, due to the cross-sectional research design, the causal factor between the thermal discomfort and occurrence of health symptoms remains unexplored. Longitudinal studies can be carried out in the future to explore the causal factor of health symptoms and OTC which is lacking in the current study. Future research can also be carried out by involving professional medical practitioners to diagnose the health symptoms as compared to using a self-reported health screening tool as such in the current study.

5.5.6 Exploring other urban heat mitigation strategies

In the current study, the UHI mitigation strategies are distinguished according to urban design and urban greening approach. In this study, a total of four case scenarios were experimented involving the addition of ground surface vegetation, the introduction of green façade, the introduction of green roof and replacing existing pavement with a cool pavement material. Future studies could be dedicated to exploring other forms of mitigation measures according to the two approaches.

5.5.6.1 Urban design

Mitigation approaches which mainly dealt with the urban form factor, surface and building material and other mechanical enhancement are referred to as urban design approach. Under the urban design approach, there are plentiful of measures yet to be explored. In terms of urban form factor, studies can be conducted to experiment on the best building orientation, aspect ratio, and other mechanical measures that could help in mitigating local UHI. In terms of surface and building material, the technology of material science currently could be further explored to produce sustainable cooling materials that would be more efficient in reducing the heat trap within a tropical city. As shown in the current study, various urban design approach to mitigate UHI can experiment through ENVI-MET software before the real-scale application in the study area.

5.5.6.2 Urban greening

The urban greening approach is related to the addition of vegetation or greeneries in both horizontal or vertical orientation to the urban area. Similarly, there are ample directions to further explore the urban greening approach to mitigate local UHI. Among some of the promising research direction are, the identification of plant types to optimally reduce UHI intensity, the abundance and placement of vegetation to optimize the urban cooling effect, and the retrofitting of buildings with vertical greenery system. Likewise, the urban greening approach can experiment beforehand with ENVI-MET software before any real-scale application in the study area.

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LIST OF PUBLICATIONS AND PAPERS PRESENTED

Journal Articles

1. **Fong, C. S.,** Aghamohammadi, N., Ramakreshnan, L., & Sulaiman, N. M. (2020). Evaluation Of Secondary School Student's Outdoor Thermal Comfort During Peak Urban Heating Hours In Greater Kuala Lumpur. Journal Of Health And Translational Medicine, 23, 3–11. Retrieved from https://jummec.um.edu.my/article/view/25806 (*Q2, IF=0.56*)
2. **Fong, C. S.**, Aghamohammadi, N., Ramakreshnan, L., Sulaiman, N. M., & Mohammadi, P. (2019). Holistic Recommendations for Future Outdoor Thermal Comfort Assessment in Tropical Southeast Asia: A Critical Appraisal. *Sustainable Cities and Society*, 101428. (*Q1, IF=5.268*)
3. Ramakreshnan, L., Aghamohammadi, N., **Fong, C. S.**, Ghaffarianhoseini, A., Wong, L. P., & Sulaiman, N. M. (2019). Empirical study on temporal variations of canopy-level Urban Heat Island effect in the tropical city of Greater Kuala Lumpur. Sustainable Cities and Society, 44, 748–762. (*Q1, IF=5.268*)
4. Ramakreshnan, L., Aghamohammadi, N., **Fong, C. S.**, Ghaffarianhoseini, A., Wong, L. P., Noor, R. M., ... & Hassan, N. (2019). A qualitative exploration on the awareness and knowledge of stakeholders towards Urban Heat Island phenomenon in Greater Kuala Lumpur: Critical insights for urban policy implications. *Habitat International*, *86*, 28-37. (*Q1, IF=4.310*)
5. Ramakreshnan, L., Aghamohammadi, N., **Fong, C. S.**, Ghaffarianhoseini, A., Ghaffarianhoseini, A., Wong, L. P., … Sulaiman, N. M. (2018). A critical review of urban heat island phenomenon in the context of greater Kuala Lumpur, Malaysia. Sustainable Cities and Society, 39, 99–113. (*Q1, IF=5.268*)
6. Ramakreshnan, L., Aghamohammadi, N., **Fong, C. S.**, Bulgiba, A., Zaki, R. A., Wong, L. P., & Sulaiman, N. M. (2017). Haze and health impacts in ASEAN countries: a systematic review. *Environmental Science and Pollution Research*, 1–16. (*Q2, IF=3.056*)
7. Ramakreshnan, L., Aghamohammadi, N., **Fong, C. S.**, & Sulaiman, N. M. (2020). Motivations and built environment factors associated with campus walkability in the tropical settings. Science of The Total Environment, 749, 141457. (*Q1, IF=6.551*)
8. Nasrin Aghamohammadi, **Chng Saun Fong**, Logaraj Ramakreshnan, Nik Meriam Nik Sulaiman (2019). A comprehensive bibliometrics of 'walkability' research

landscape: Visualization of the scientific progress and future prospects. (*ISI-Indexed*) – **Submitted**

9. Nasrin Aghamohammadi, Amirhosein Ghaffarianhoseini, **Chng Saun Fong**, Logaraj Ramakreshnan, LP Wong, nikmeriam niksulaiman, Noor Rosly Hanif, Norhaslina Hassan, Rafidah Md Noor, Wan Nor Azriyati Wan Abd Aziz (2019). Perceived impacts of Urban Heat Island phenomenon in Greater Kuala Lumpur: Perspectives from stakeholder dialogue sessions. (*ISI-Indexed*) – **Submitted**
10. Aghamohammadi, N., Muniratul Husna Mohd Idrus, **Fong, C. S.**, Ubydul Haque, Logaraj Ramakreshnan (2020). Outdoor thermal sensation and somatic symptom severity among the students in a tropical city. (*ISI-Indexed*) – **Submitted**

Conference proceedings

1. **(Oral) Chng Saun Fong,** Nasrin Aghamohammadi, Logaraj Ramakreshnan, Nik Meriam Sulaiman (2019). Evaluation of Secondary School Student's Outdoor Thermal Perceptions during Peak Urban Heating Hours in Kuala Lumpur. In Asia-Pacific Academic Consortium for Public Health-Kuala Lumpur (APACPH-KL) at Kuala Lumpur, 11th – 12th April 2019.
2. **(Poster)** Logaraj Ramakreshnan, Nasrin Aghamohammadi, **Chng Saun Fong,** Nik Meriam Sulaiman (2019). Are the stakeholders really aware of Urban Heat Island? Perspectives of urban policy relevance from Expert Sharing Sessions in Greater Kuala Lumpur. In Asia-Pacific Academic Consortium for Public Health-Kuala Lumpur (APACPH-KL) at Kuala Lumpur, 11th – 12th April 2019.
3. **(Oral) Chng Saun Fong,** Nasrin Aghamohammadi, Nik Meriam Sulaiman (2018). Urban Greening and Design Simulation for the Enhancement of Urban Microclimate and Outdoor Thermal Comfort. In Wild and Wise Collaborative Learning Programs at Kyoto University, Kyoto, Japan, 21st October 2018 – 3rd November 2018.
4. **(Poster) Chng Saun Fong**, Nasrin Aghamohammadi, Logaraj Ramakreshnan, Nik Meriam Sulaiman, Wong Li Ping (2018). Urban Heat Island Phenomenon and Deterioration of Outdoor Thermal Comfort as an Emerging Threat to Tropical Cities. In Wild and Wise Collaborative Learning Programs at Kyoto University, Kyoto, Japan, 21st October 2018 – 3rd November 2018.
5. **(Oral) Chng Saun Fong,** Nasrin Aghamohammadi, Logaraj Ramakreshnan, Nik Meriam Sulaiman (2018). The Deterioration of Outdoor Thermal Comfort as an Emerging Threat to Tropical Cities – A Review. In the 12th APRU Global Health

Conference 2018: Planetary Health - The Next Frontier, Kuala Lumpur, 28th-30th October 2018.

6. **(Poster)** Aghamohammadi, N., Ramakreshnan, L., **Chng Saun, F.**, Sulaiman, N. M. N. & Li Ping, W., Hoseini, A. G. (2017). Heat Waves and Community Health: The Case of Greater Kuala Lumpur. In The 5th AHLA International Health Literacy Conference: Health Literacy and Population Health, Kuala Lumpur, 12–14 November 2017.
7. **(Poster)** Nasrin Aghamohammadi, **Fong Chng Saun**, Logaraj Ramakreshnan, Saeid Alizadeh, Mohammad Reza Khosravi & Nik Meriam Sulaiman (2018). Smart IOT Metering System (SIMS) As an Integrated Tool for Sustainable Energy Consumption. In the International Research Innovation, Invention & Solution Exposition (IRIISE) at Expo on University Research Invention, Creation & Innovation (EUREKA) 2018

Chapter in book

1. Nasrin Aghamohammadi, Logaraj Ramakreshnan, **Chng Saun Fong**, Nik Meriam Sulaiman. Climate-related disasters and health impact in Malaysia (2018) Editor: Rais Akhtar. EXTREME WEATHER EVENTS AND HUMAN HEALTH Switzerland: Springer Nature

Books

1. **Fong Chng Saun**, Nasrin Aghamohammadi, Logaraj Ramakreshnan, Nik Meriam Sulaiman, Wong Li Ping, Rafidah Noor, Noor Rosly Hanif (2018) Climate literacy: Influence of Urban Design and Greening on Urban Microclimate, COEHUM Publisher, 30p.
2. Logaraj Ramakreshnan, Nasrin Aghamohammadi, **Fong Chng Saun**, Nik Meriam Sulaiman, Wong Li Ping, Rafidah Noor, Noor Rosly Hanif (2018) Climate literacy: a primary move to expand the frontiers of climate education, COEHUM Publisher, 25 p.

Publication - Other (Articles in magazine, newspaper etc.)

1. **Fong, C.S.** (2018, April 12). Seminar on 'Climate Change and Sustainable Governance: Cooling KL City'. Retrieved from https://spm.um.edu.my/2018/04/12/seminar-on-climate-change-and-sustainable-governance-cooling-kl-city/
2. **Fong, C.S.** & Aghamohammadi, N. (2019) The deterioration of outdoor thermal comfort as an emerging threat to tropical cities. UM Research Bulletin Vol. 19, No.1, 2019, Pg. 32-33.

Intellectual properties (Patent/Copyright/Trademarks etc)

1. Utility innovation application no.: UI 2020000785. Utility Innovation Patent Name: Real Time Heat Index and Air Quality Monitoring System (HI-AQMS). Inventors & co-inventors: Nasrin Aghamohammadi, **Fong Chng Saun**, Logaraj Ramakreshnan, Saeid Alizadeh, Mohammad Reza Khosravi.
2. Copyright filing no.: LY2020003031. Climate Literacy: Influence of Urban Design And Greening On Urban Microclimate. Inventors & co-inventors: **Fong Chng Saun**, Nasrin Agha Mohammadi, Logaraj Ramakreshnan, Nik Meriam Binti Nik Sulaiman.
3. Copyright filing no.: LY2020003030. Climate Literacy: A Primary Move to Expand The Frontiers Of Climate Education. Inventors & co-inventors: Logaraj Ramakreshnan, Nasrin Agha Mohammadi, **Fong Chng Saun**, Nik Meriam Binti Nik Sulaiman.