The Study of Vegetation Effects on Reduction of Urban Heat Island in Dubai

دراسة دور الغطاء النباتي في الحد من آثار الجزر الحرارية الحضرية في دبي

By
Tahereh Rajabi

Student ID **90062**

Dissertation submitted in partial fulfillment of MSc. in Sustainable Design of the Built Environment

Faculty of Engineering and IT

Dissertation Supervisor

Professor Bassam Abu-Hijleh

December 2011

بسم الله الرحمن الرحيم

In the name of Allah,
the Most Beneficent,
the Most Merciful

APPENDIX A
STUDENT DISSERTATION RECEIPT

Programme [ ] Submission Date [ ]

Student ID [ ] Supervisor [ ]

Submission purpose: Marking [ ] Final [ ]

No. of hardcopies Soft copy format

Softcopy submitted to: [ ]

DECLARATION

I confirm that I have read and understood the University Policy on Academic Honesty and that the work contained in the attached dissertation is my own work. Any assistance, of any type, has been acknowledged in my bibliography.

I also understand that the university may use plagiarism detection software on any submitted work, whether plagiarism is suspected or not.

I **do hereby consent/ do not consent (delete as applicable)** that my work is submitted into the plagiarism detection software to check the originality of my work.

______________________________ ______________________________
Signature Date

Collected by: ________________________________ Date: ______________________

In case of CD-ROM Collected by Library: CD-ROM forwarded to: ______________

Signature of Receipt _________________________ Date: ______________________

- -

FOR LIBRARY USE ONLY

STUDENT DISSERTATION RECEIPT

Student ID: Date of submission:

Received by: Signature:

Official stamp:

Abstract

Rapid urbanization in the past 100 years has resulted in many environmental issues in large cities. Urban Heat Island which is the condition of excess heat in city centers is one of these environmental issues. Dubai which has developed tremendously in the past decade also suffers from condition of urban heat island. This research aims to study the effects of vegetation on reduction of urban heat island in dense and old neighborhoods of Dubai.

Computer simulation was selected as the major methodology in this research and ENVI-met software was utilized as the main simulation tool. The investigations in this research were performed in two parts; Part One focused on identifying the most effective strategies of applying greenery in a simplified urban condition. In Part Two, these strategies were applied on two urban blocks in Dubai to measure their effectiveness on real conditions.

The results from both parts of the research showed that application of trees with medium density is the most effective strategy in tackling excess heat in urban areas. Also, it was concluded that both grass and green roofs have negligible effects on reducing surface temperatures in the urban areas. Based on the results, it is suggested to apply the medium density trees in compacted forms around the built up structures in newly designed urban areas. In terms of the pre-existing urban areas, the best strategy is to utilize available empty plots such as parking lots to insert compacted forms of medium density trees in addition to planting along the wide pedestrian and vehicular paths.

ملخص

نتج عن التحضر والتطور المدني السريع في آخر 100 عام العديد من المشاكل البيئية في المدن الكبيرة. فالجزر الحرارية الحضرية التي تعتبر حالة من الحرارة الزائدة في مراكز المدن هي إحدى هذه المشاكل البيئية. ودبي التي تطورت بشكل كبير جداً في العقد الماضي تتأثر أيضاً جراء حالة الجزر الحرارية الحضرية. وهذا البحث يهدف لدراسة تأثيرات الحياة النباتية على التخفيض من الجزر الحرارية الحضرية في المناطق ذات الكثافة السكانية العالية جداً والمناطق القديمة في دبي.

تم اختيار محاكاة الحاسوب كمنهجية رئيسية في هذا البحث وتم استخدام برنامج انفي- ميت كأداة المحاكاة الرئيسية. وتم أداء الفحوصات في هذا البحث في جزأين؛ يركز الجزء الأول في التعرف على أكثر الاستراتيجيات تأثيراً في استخدام النباتات الخضراء في حالة مدنية مبسطة. وفي الجزء الثاني، تم تطبيق هذه الاستراتيجيات على حيين مدنيين في دبي لقياس تأثيرها على الحالات الحقيقية والواقعية.

أظهرت النتائج من كلا جزأي البحث بأن استخدام الأشجار ذات الكثافة المتوسطة هو الاستراتيجية الأكثر فعالية في معالجة الحرارة الزائدة في المناطق المدنية. وتم الاستنتاج أيضاً بأن العشب والأسطح الخضراء ليس لها تأثيرات تذكر في التخفيض من درجات الحرارة في المناطق المدنية. وبناء على هذه النتائج، تم اقتراح استخدام الأشجار متوسطة الكثافة على أشكال مرصوصة حول الهياكل المبنية في المناطق المدنية المصممة حديثاً. وبالنسبة للمناطق المدنية القديمة، فأفضل استراتيجية هي استخدام قطع الأراضي الفارغة المتوفرة مثل مواقف السيارات لإدخال الأشكال المرصوصة للأشجار المتوسطة الكثافة إضافة إلى زرعها على طول ممرات المشاة وطرق المركبات.

ACKNOWLEDGMENT

First of all, I would like to thank *Allah*, the most gracious and the most merciful, for all His blessings and gifts to me. I have truly felt His presence with love and care in every moment of my life including the period I worked on this dissertation.

This dissertation would have not been possible without the guidance of my wise instructor and advisor, *Professor Bassam Abu-Hijlah*. I truly cherish the opportunity of being his student and appreciate his endless enthusiasm, inspiration and support throughout the project.

I gratefully acknowledge the family of British University in Dubai and specifically my professors *Dr. Abeer Shahin* and *Dr Fadeyi Moshood Olawale* for providing me with the essential support and knowledge to start this dissertation.

I would like to extend my gratitude to *Mr. Ahmed Mohammed Abdulla Al Jassmi* and *Mr. Narciso M. Zacarias* from “Environment Department” of Dubai Municipality for facilitating me with some crucial recourse possessed by *Dubai Municipality*.

Words fail to express my thankfulness to *Mr. Jamil Behzad*, for being a true friend, motivator and source of inspiration. It has been extraordinarily fortunate to have such a supportive and kind-hearted person beside me all along.

Last but never the least; I thank my little sister *Masoomeh Rajabi*, who has been the best friend and certainly a true gift from Allah beside the rest of family. I appreciate all the support and efforts she patiently provided for me throughout the project and acknowledge her true love in my heart.

I dedicate this Dissertation to my Mother and my Father; to my three Sisters and three Brothers. I am nothing without you and your prayers…

این تحقیق را تقدیم می‌کنم به مادرم و به پدرم؛ به سه خواهرم و سه برادرم؛

بی شما و دعاهایتان هیچم...

Table of Contents

List of Figures

List of Tables

CHAPTER 1

Introduction

1.1 History of Urbanization

The history of the first cities in the world goes back to the ancient times when the advancements in ability to create permanent structures and shelters allowed humans to settle down in villages and cities. These historic cities used to be important centers for politics, business, health care and education with a natural growth of the population. However, at the turn of 19^{th} century cities faced unnatural growth and their populations increased decade by decade and they began to face challenges of rapid urbanization. Industrialization and advancement in technology caused the growth of cities based on two factors; first was the ability to relocate population faster by steam trains and ships and the second was economic growth in the cities which provided better jobs and incomes for the loads of population. Therefore the population of the cities began to grow faster and faster and the modern urban areas came to existence. The trend of global urbanization which started at the turn of 19^{th} century continued at its fastest rate in the history; according to United Nations. Dept. of Economic and Social Affairs during the second half of 20^{th} century, the world's urban population increased at an average annual rate of 2.72 percent implying that it doubled every 25 years and in the year 2000, the total population of the cities around the world was estimated to be 2.9 billion. According to the information provided in Table 1.1(a), the world's urban population is still increasing and estimated to reach 6.3 billion in 2050. Even though Table 1.1 (c) indicates that the annual growth rate of urban population is decreasing, the estimation of 70 percent urban population for 2050 is an indisputable fact which demands proper planning and preparation.

Rapid urbanization has caused number of negative consequences in different parts of the world. In general, the negative impacts of urbanization range from social and economic problems to environmental consequences. For example, slum development in mega cities of the third world countries is one of the most important problems of rapid urbanization which results in social deprivation, poverty, poor sanitation and lack of education. Plus rapid urbanization reinforces the economic burden of improving the city's infrastructure to meet the increased demand in water and electricity supply, sewage and garbage collection, improvement of public facilities as well as roads and transport infrastructure.

Table 1.1 World Urbanization Prospect. (a) Urban population (thousands) 1950-2050; (b) Percentage urban (%) 1950-2050; (c) Urban annual growth rate (%) 1950-2050. (United Nations. Dept. of Economic and Social Affairs)

Year	Urban population
1950	736 796
1955	854 955
1960	996 298
1965	1 160 982
1970	1 331 783
1975	1 518 520
1980	1 740 551
1985	1 988 195
1990	2 274 554
1995	2 557 386
2000	2 853 909
2005	3 164 635
2010	3 494 607
2015	3 844 664
2020	4 209 669
2025	4 584 233
2030	4 965 081
2035	5 341 341
2040	5 708 869
2045	6 063 186
2050	6 398 291

(a)

Year	Percentage urban
1950	29.1
1955	30.9
1960	32.9
1965	34.7
1970	36.0
1975	37.3
1980	39.1
1985	40.9
1990	43.0
1995	44.7
2000	46.6
2005	48.6
2010	50.6
2015	52.7
2020	54.9
2025	57.2
2030	59.7
2035	62.2
2040	64.7
2045	67.2
2050	69.6

(b)

Year	Urban annual growth rate
1950-1955	2.97
1955-1960	3.06
1960-1965	3.06
1965-1970	2.75
1970-1975	2.62
1975-1980	2.73
1980-1985	2.66
1985-1990	2.69
1990-1995	2.34
1995-2000	2.19
2000-2005	2.07
2005-2010	1.98
2010-2015	1.91
2015-2020	1.81
2020-2025	1.70
2025-2030	1.60
2030-2035	1.46
2035-2040	1.33
2040-2045	1.20
2045-2050	1.08

(c)

Besides all these socio-economic challenges, cities have faced number of environmental challenges as well, that not only decreased the quality life in the urban areas but also contributed to global climate change and the deterioration of natural resources worldwide. The environmental problems occur at different layers in the cities; for example one layer is related to pollution and includes air, water, sound and solid waste pollution. Each of these consequences listed under pollution, affects the health and well being of every city residents exposed to them. One of the most important factors that affect the pollution related problems is existence of industries within the cities. Industrial pollution which can be very hazardous contributes to the air pollution through the exhaust of hot air that contains high concentrations of toxic gases such as CO_2 in the air. Also they cause water and solid waste pollution by disposing toxic wastes into the liquid sewage networks or solid waste dump sites. Industries also cause noise pollution through the noise produced by their machines and other activities. Factors other than industries cause pollution in the cities as well; for example in some cities high concentrations of households and business units that are not served by the city's sewage system greatly add to water and solid waste pollution in the urban areas. One of the most common example of this factor are slums which exist in high concentrations in many third world countries and highly contribute to the pollution in these cities. Plus local climatic conditions also contribute to pollution in the cities (particularly air pollution). One of the most common incidences of this factor is thermal inversion which is the condition of a layer of warm air covering and trapping the polluted cold air layer in an urban area during winter. Also many cities lack wind which would help to scatter the air pollution caused by high concentrations of automobiles and industries in urban areas.

Deterioration of natural resources is another environmental challenge which has caused the loss of water resources, forests, soils, lakes and fisheries around the cities and caused number of other problems globally. One of the most incidents of this environmental problem is urban sprawl which is basically the expansion of urban areas to suburbs and rural areas. Urban sprawl has caused serious environmental problems such as deterioration of land and water resources due to construction of new households and roads. Other factors include excessive usage of underground water resources by the residents as well as destruction of green areas around the cities and construction of roads and buildings.

Each of the challenges mentioned above is a wide topic of research which is not the focus of this study. This research focuses on a phenomenon known as Urban Heat Island; Urban Heat Island is one of the most important challenges of rapid urbanization which happens at the microclimatic level in the urban areas. This phenomenon is characterized as a warmer inner urban areas compared to cooler suburban areas of a city. There are several causes, consequences and mitigation strategies related to this phenomenon which would be discussed in detail next chapter.

1.2 History and Definition of Urban Heat Island

The first records of the study of Urban Heat Island dates back to 200 years ago when Luke Howard, a British manufacturing chemist and an amateur meteorologist launched a pioneering research on climate of London. Howard found an artificial condition of higher air temperature in London compared to countryside in 1818 and marked the first measure of Urban Heat Island in history. In his book ‘the climate of London” he accurately associated the higher temperature in the city center with human and heat from combustion of fuels in winter, and absorption and release of solar heat by urban surfaces during summer (Howard, 1833). After Howard other scientists such as Emilien Renou discovered similar situation in Paris during the second half of the 19th century. Also some other scientists continued to study urban climatology in cities such as Vienna during the first half of 20th century. Since then, the study of Urban Heat Island has become a specific field in environmental studies and scientists have studies its aspects in more details.

Urban heat island can be defined as a temperature variance where an urban area (normally located at the heart of the city) features an island of warmer air and surface temperature compared to a suburban or rural area which features a sea of cooler air and surface temperature. The heat island normally exhibits four main characteristics (Gartland, 2008):

- Heat Island Intensity with hourly changes
- Larger effects during calm and clear weather conditions

- Larger effects in more developed and dense areas
- Thermal inversions

1.2.1 Heat Island Intensity With Hourly Changes

The first and foremost characteristic of UHI is the hotter air temperature of the inner urban areas compared to surrounding rural areas. The difference in temperature of these two areas is called Heat Island Intensity or Strength which is used to measure and analyze the UHI. Heat Island Intensity varies throughout the day and night; for example the intensity rate exhibits its least amount in the early morning because at this time all the stored heat in surfaces from the previous day, has been released. However, the heat island intensity increases throughout the day as heat is stored in urban surfaces, and reaches its peak during late afternoon hours, when the urban surfaces begin to omit the stored heat into the surrounding air. Even though this hourly variation is common in all cities that feature urban heat islands; its magnitude is different from one city to another. This magnitude is directly affected by the causes of Urban Heat Islands in different cities which would be explained in the coming sections.

1.2.2 Larger Effects During Calm and Clear Weather Conditions

The urban heat island effect increases during calm and clear sunny days. As the urban surfaces are more exposed to the sun during the sunny days and slower winds circulate less air in urban areas, the urban heat island increases in these areas. On the other hand, urban heat island is less intense during cloudy, windy days because the surfaces would gain less heat from the sun and stronger winds would circulate the hot air at a faster rate. Figure 1.1 shows the hourly temperature difference for the city of Bucharest in Romania in year 1994 (Gartland, 2008). Graph (a) exhibits temperature variations for spring (solid), summer (dashed) and winter (dotted) for a cloudy and windy day in Bucharest while graph (b) shows the same parameters for a sunny and calm day. It is clear that the weather condition has a significant effect on the magnitude of Heat Island Intensity since during a cloudy day in summer, the peak intensity reaches about 1^0C while during a sunny day in summer, the peak intensity reaches almost 3^0C in Bucharest.

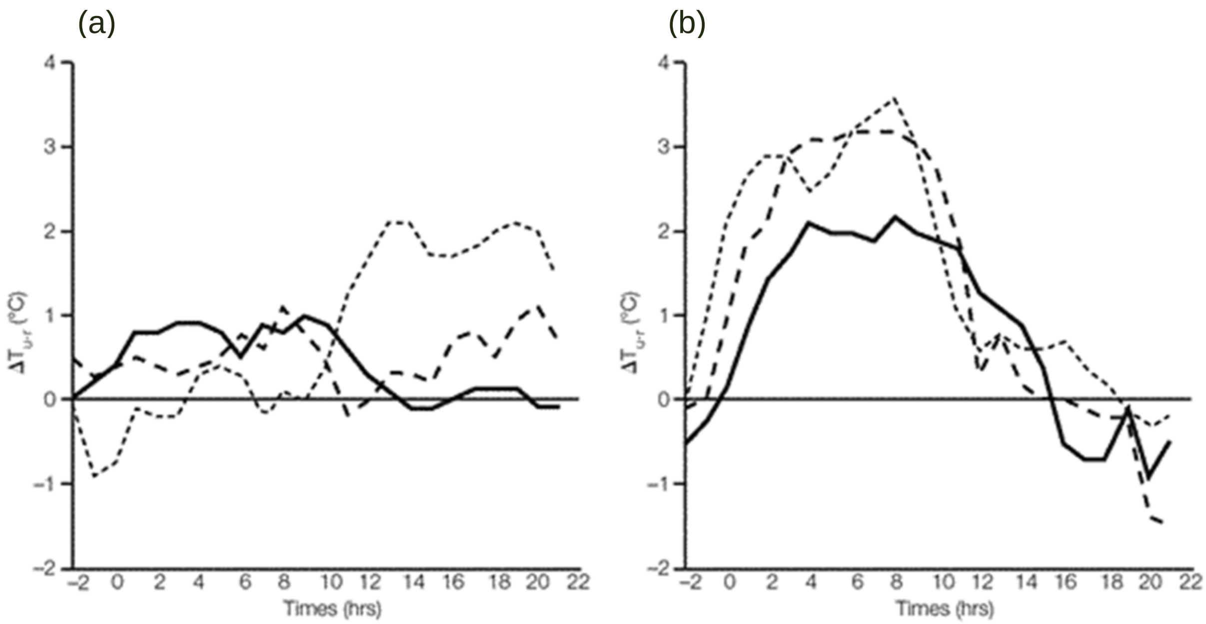


Figure 1.1 Heat Island Intensity for a cloudy (a) and sunny (b) weather condition in the city of Bucharest, Romania. (Gartland, 2008)

Kolokotroni and Giridharan (2008) have also studied the effect of physical characteristics and weather conditions on the intensity of urban heat island in London. The climatic conditions are divided into three categories of clear sky, partially cloudy and cloudy in this study. Figure 1.2 shows a comparison of urban heat island intensity for these different categories of weather condition during summer 2000. Both diurnal and nocturnal variations exhibit highest UHI intensities under clear sky condition while showcasing lowest levels under cloudy conditions. Therefore the weather condition is one of the factors that have direct effect on creation of urban heat island.

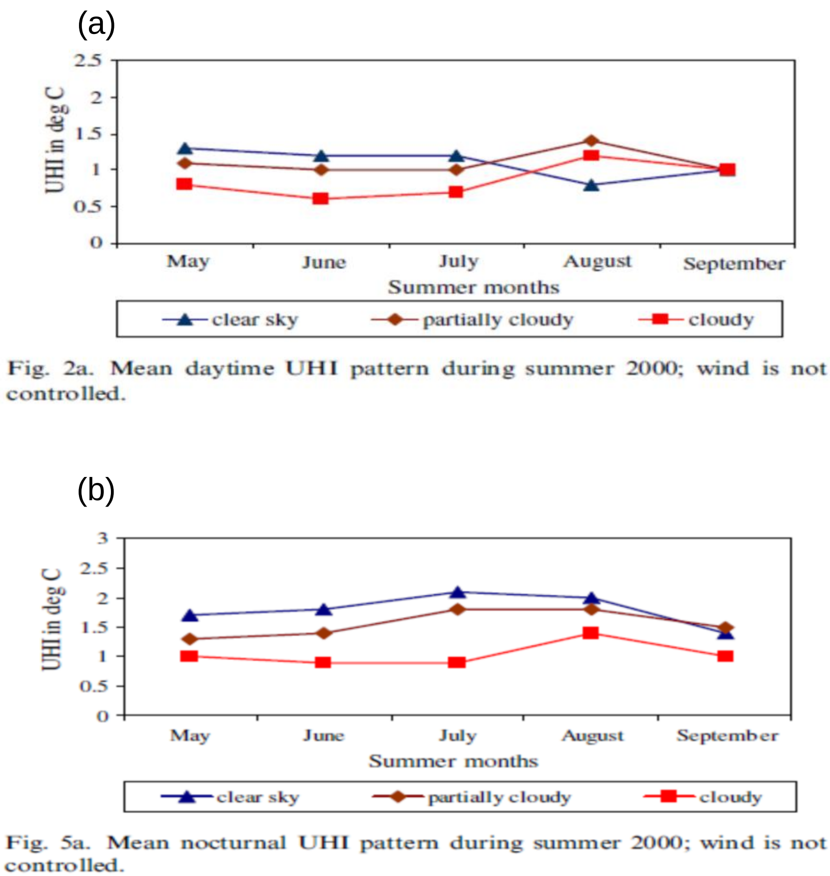


Figure 1.2 Mean UHI Pattern during Summer 2000 in London. (a) Diurnal variations; (b) Nocturnal variations.(Kolokotroni and Giridharan , 2008)

1.2.3 Larger Effects in More Developed and Dense Areas

The other characteristic of UHI is its direct relationship with developments in the cities; as the urban and sub urban areas develop in time, the intensity of UHI increases as well. This is due to the fact that larger and denser urban areas store more heat as exposed to heat sources and as a result, release larger amounts of heat as their exposure to the heat sources decrease. Figure 1.3 shows an isotherm map of air temperature for the city of Tel-Aviv during afternoon and evening hours (Saaroni, H. et al, 2000). The gradient of the temperature increases as the contours get closer to the city center showcasing the highest temperatures in the denser areas in the city. In general the urban heat island came to existence in developing cities at the turn of the 19th century, when cities started to develop at a higher and denser rate. Today in many cities this phenomenon is turning into a serious dilemma as the urban areas develop at a larger and denser scale.

1.2.4 Thermal Inversions

The air around urban areas is divided into two layers, one is the canopy layer which is closer to the ground and the other is the boundary layer which is at higher altitudes above the canopy layer. Naturally, the warmer canopy air moves up at a constant circulation rate and is replaced by a cooler air from

(a) (b)

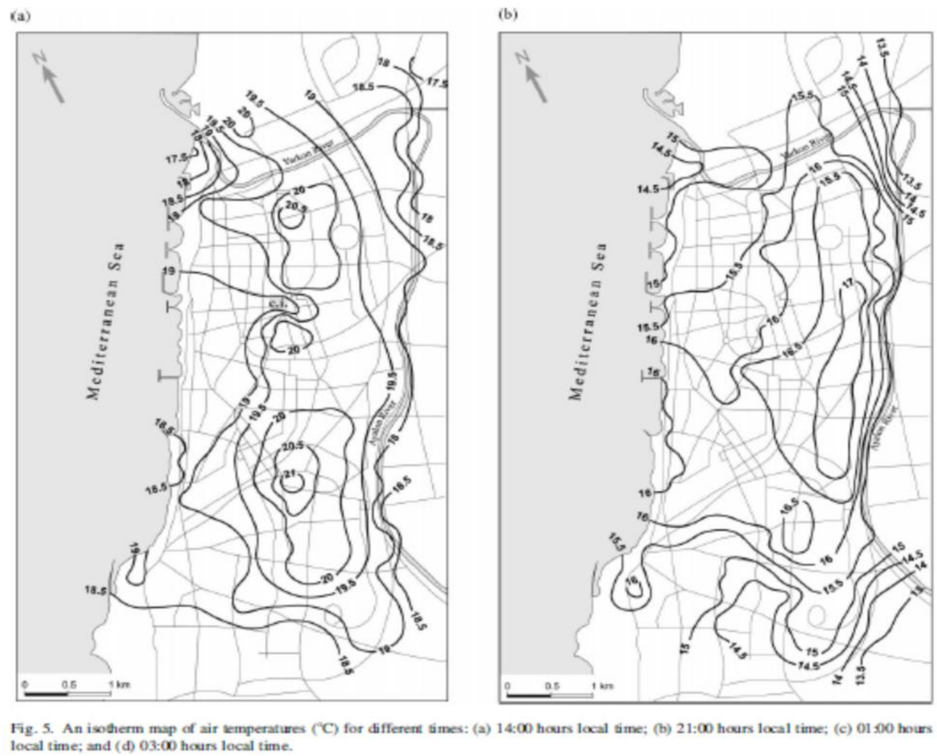


Figure 1.3 An isotherm map of air temperatures for different times in city of Tel- Aviv; (a) 14:00 local time; (b) 21:00 local time.(Saaroni, H. et al, 2000)

the boundary layer. However this natural phenomenon sometimes turns into a challenge called thermal inversion. Urban heat Island works in favor of this phenomena in a lot of cases, were a layer of overheated air from the canopy layer rises into the higher altitudes and traps a cooler layer of dusty and polluted air at lower altitudes.

This phenomenon is specially evidence in the dense urban areas during the night time when the urban surfaces have lost most of their heat during the first few hours after the sunset, and heating the air happens at a slower rate by these surfaces. In order to measure the effect of urban heat island on thermal inversions, the air temperature should be measured at different elevations moving from the city center to the rural areas. A good example of this study was done by Bornstein in 1968; Figure 1.4 shows the horizontal and vertical temperature distribution at early morning of a summer day in New York City (Bornstein,1968). In this graph, highest air temperatures close to the surface are mapped around the city center while lowest temperatures are mapped in rural areas indicating the existence of urban heat island. On the other hand strong level of thermal inversion is mapped around the central area at high elevations while the thermal inversion in rural areas exists at lower elevations. Therefore both horizontal and vertical temperatures indicate a relationship between urban heat island and thermal inversions in this graph.

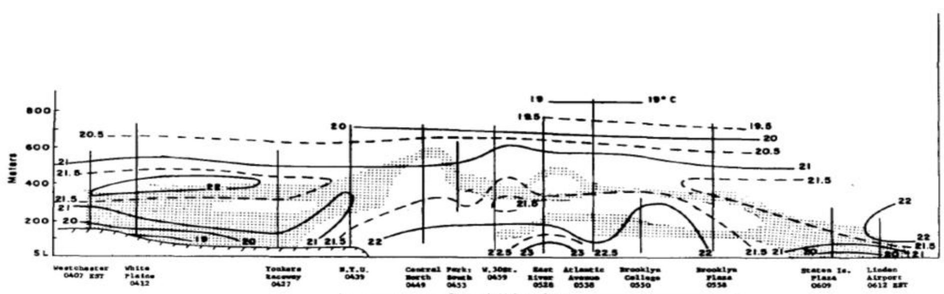


FIG. 3. Vertical and horizontal temperature distribution over the New York City area on 16 July 1964 from 0407–0612 EST.

Figure 1.4 Vertical and horizontal distribution of temperature over New York City on July 1964. (Bornstein,1968)

1.3 Causes of Urban Heat Island

In the previous section, the characteristics of UHI were discussed in detail however the causes or factors that lead to this phenomenon were not mentioned. Before going into more detail with the causes of UHI it is worthy to determine the sources of heat in an urban area. There are two sources of heat gain in urban areas; sun and anthropogenic sources. Urban areas gain heat from the sun through solar radiation while getting heat from anthropogenic sources through people, machinery and buildings. According to the first law of thermodynamic, energy is not produced nor lost in nature therefore the heat that is gained through these sources is reflected back into the environment in different forms. Equation 1.1 is the energy balance equation for the urban areas (Gartland, 2008).

$$\text{Anthropogenic Heat} + \text{Solar Radiation} = \text{Convection} + \text{Evaporation} + \text{Storage} \quad (1.1)$$

According to this equation the heat gained by urban surfaces is transferred into the environment in three ways. First is convection in which the heat is transmitted into the surrounding air through convection from a solid (urban surface) into a fluid (surrounding air). Second is through evaporation in which the energy is shifted away from the surfaces by water vapor. Third is heat storage which is directly associated with thermal capacity of the material, that is the ability of a material to store and retain heat in its mass. The relationship of this equation and UHI is that smaller magnitudes of convection and evaporation in correlation to larger magnitudes of Anthropogenic heat, solar radiation and heat storage result in creation of the urban heat island phenomenon. Therefore the factors contributing to urban heat island are directly related to each of the parameters in this equation; these factors are as follow:

1. Evaporation within the urban areas
2. Urban Materials
3. Urban geometry
4. Anthropogenic heat
5. Air pollution

Each of these factors causes the creation of UHI in its own specific way and therefore demands its own analysis and mitigation strategy.

1.3.1 Evaporation Within the Urban Areas

Moving from the rural to suburban and urban areas, the amount of vegetation and permeable surfaces decreases and instead the amount of impervious surfaces increases. Figure 1.5 (Voiland, 2010) is a satellite image of the city of Providence in the Unites States which shows the effect of reduced evaporation. The first image maps the developed land in a range of red color which increases as moved from surrounding rural areas to the city center; the bulk of red color in the center of the image could also be interpreted as the amount of solid impervious surfaces. The second image depicts vegetation in a range of green color which drastically decreases from the surrounding rural areas to the city center; likewise the light green color in the center of the image could be interpreted as impervious surfaces in the city center. The third image shows the surface heat in a range of violet color which increases significantly from the surrounding to the city center. Comparison of these three images shows a direct relationship between the reduction of vegetation and permeable surfaces with increase in surface heat of the central urban areas.

The reason behind this behavior is the fact that as the permeability of a surface decreases its ability to release the heat gain decreases as well. Therefore the impervious surface stores and retains the heat throughout day causing an increase in surface temperature. On the other hand, the stored heat is released to the environment during the night through higher radiant emissions and convection. However it is worthy to note that lower levels of evaporation are not the primary cause of urban heat island and factors other than evaporation play primary role in creation of urban heat island in some cities.

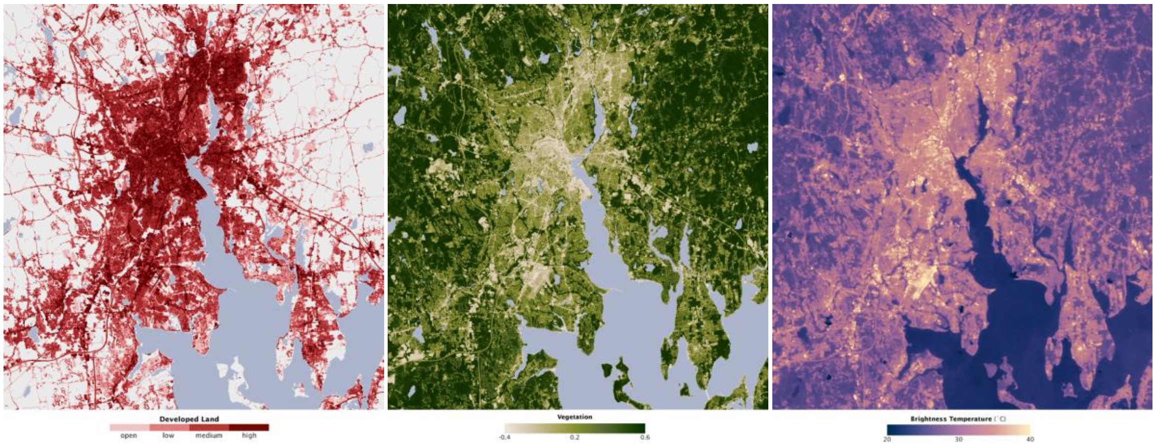


Figure 1.5 Satellite images of Providence, Rhode Island in United States. From left to right: Developed Land, Vegetation and Surface Heat. (Voiland, 2010)

1.3.2 Urban Materials

The next factor which has significant effect on creation of UHI is the properties of materials that are used to build up the pavements, walls, roads and roofs in the urban areas. There are four main properties that cause an increase in the surface temperature of a material. The first two which are related to heat storage in a material, are Thermal Conductivity and Heat Capacity (Table 1.2). Thermal conductivity is the ability of a material in conducting heat into its depth while heat capacity refers to ability of a material to store heat in its bulk. The effect of these two properties is reflected in a third parameter known as thermal diffusivity which is found as the division of a material's thermal conductivity by its heat capacity. Therefore, Thermal diffusivity is the ability of a material to conduct heat into its depth and retain this heat over a longer period of time. For example the thermal diffusivity of dense wood (a material found in nature) is 0.13 $m^2/s \times 10^{-6}$ while the thermal diffusivity of concrete (a common material in urban areas) is 0.72 $m^2/s \times 10^{-6}$ (Wang, 2000). This means that concrete is able to conduct and store heat at a larger rate compared to dense wood; and this is the reason why materials such as concrete, roof tiles, pavement tiles, steel, brick and stone tend to rise the temperature in the urban areas.

Table 1.2 Thermal Properties of Selected Urban Materials (Wang, 2000)

	Density, lb/ft^3	Thermal conductivity, $(Btu/h \cdot ft \cdot °F)$	Specific heat, $(Btu/lb \cdot °F)$	Emissivity	
Aluminum (alloy 1100)	171	128	0.214	0.09	
Asbestos: insulation	120	0.092	0.20	0.93	
Asphalt	132	0.43	0.22		
Brick, building	123	0.4	0.2	0.93	
Brass (65% Cu, 35% Zn)	519	69	0.09	0.033	Highly polished
Concrete (stone)	144	0.54	0.156		
Copper (electrolytic)	556	227	0.092	0.072	Shiny
Glass: crown (soda-lime)	154	0.59	0.18	0.94	Smooth
Glass wool	3.25	0.022	0.157		
Gypsum	78	0.25	0.259	0.903	Smooth plate
Ice (32°F)	57.5	1.3	0.487	0.95	
Iron: cast	450	27.6	0.12	0.435	Freshly turned
Mineral fiberboard:					
acoustic tile, wet-molded	23	0.035	0.14		
wet-felted	21	0.031	0.19		
Paper	58	0.075	0.32	0.92	
Polystyrene, expanded, molded beads	1.25	0.021	0.29		
Polyurethane, cellular	1.5	0.013	0.38		
Plaster, cement and sand	132	0.43		0.91	Rough
Platinum	1340	39.9	0.032	0.054	Polished
Rubber: vulcanized, soft	68.6	0.08	0.48	0.86	Rough
hard	74.3	0.092		0.95	Glossy
Sand	94.6	0.19	0.191		
Steel (mild)	489	26.2	0.12		
Tin	455	37.5	0.056	0.06	Bright
Wood: fir, white	27	0.068	0.33		
oak, white	47	0.102	0.57	0.90	Planed
plywood, Douglas fir	34	0.07	0.29		
Wool: fabric	20.6	0.037			

The third property is the Emittance of a material which is defined as its ability to emit the absorbed heat through radiation. It measures on a scale of 0-1 and explains how well a surface radiates heat away from itself compared to a black body which stores all the heat (black body has the e value of 1). Table 1.3 shows the Emittance of some of the materials found in the urban areas; for example Aluminum sheet has the e value of 0.12 while building materials such as masonry have the e value of 0.9; This means Aluminum sheet has a higher ability to radiate the heat back while building materials have a much lower ability in doing so and therefore tend to store most of the absorbed heat. As a result, the high Emittance value of most materials in the urban areas such as masonry, concrete and asphalt works in favor of UHI in these areas.

Table 1.3 Average Emittance of materials found in urban areas (ASHRAE, 2004)

Surface	Average Emittance *e*
Aluminum foil, bright	0.05
Aluminum foil, with condensate just visible (>0.5 g/m^2)	0.30
Aluminum foil, with condensate clearly visible(>2.0 g/m^2)	0.70
Aluminum sheet	0.12
Aluminum coated paper, polished	0.20
Steel, galv., bright	0.25
Aluminum paint	0.50
Bldg materials: wood, paper, masonry, nonmetallic paints	0.90
Regular glass	0.84

The forth property of the materials that have a direct effect on creation of UHI effect is Solar Reflectance or Albedo which is the ability of a material to reflect the solar radiation back to the surrounding environment. This property which measures on a scale 0-1 has higher values for the materials found in nature and lower value for materials found in urban areas. As shown in Figure 1.6, asphalt and built up roofing which are mostly used in urban areas have lower reflectance value ranges compared to natural materials such as grass. Therefore the prominent use of low reflectance value materials contributes to the effect of UHI in the urban areas.

1.3.3 Urban Geometry

The next factor which affects the creation of UHI is the geometry of urban fabric. This factor is especially effective in the dense areas where a lot of surfaces such as walls, windows, roof, pavements and roads are facing one another in many directions. This density causes the surfaces to radiate the heat onto one another rather than giving it off to the atmosphere. For example a pavement trapped between several tall buildings not only receives radiated heat from walls of these building but also is incapable of releasing the heat gain back to the atmosphere. The other obstacle created by urban geometry in favor of UHI is reduction of wind speed in the urban areas compared to rural areas. The building and house blocks act as wind breaks and reduce the effect of heat exchange of urban surfaces through convection in these areas.

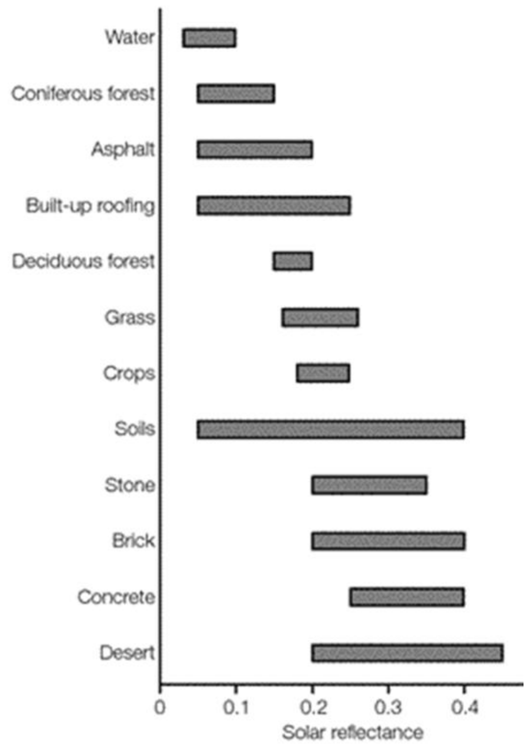


Figure 1.6 Solar Reflectance of Materials (Gartland, 2008)

The effect of urban geometry on surface temperatures is often discussed through a parameter called sky view factor. SVF is defined as the amount of the visibility of the sky from a given point on surface and it can be measured on a scale of 0 to 1. For example a parking lot in the middle of an open space has a SVF value close to 1 because of minimum obstructions in the sky. Figure 1.7 shows the surface and air temperature variations as moved from a dense area to an open area. As shown in Figure 1.7, moving from area 1 to area 8 the sky view factor of the urban canyon varies which has a direct effect on surface temperature; for example area 1-2 which has svf value of 0.34 has significantly higher surface temperature compared to area 8 with svf value of 0.85.

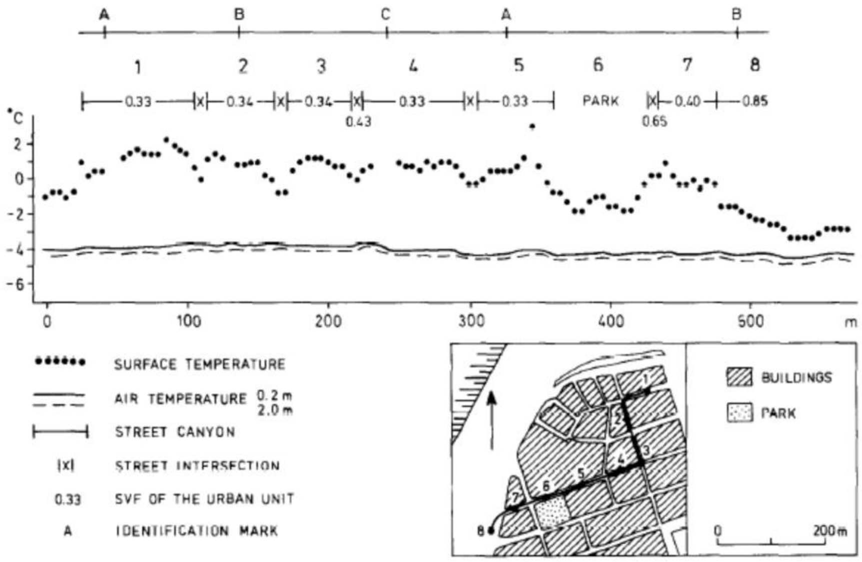


Fig. 8. Automobile traverse in the northern part of the city centre. Profiles of surface temperatures and air temperatures at 0.2 and 2.0 m.

Figure 1.7 Automobile traverse in the northern part of the city of Goteborg, Sweden. Profiles of surface temperatures and air temperatures at 0.2 and 2.0 m. (Eliasson, 1995)

1.3.4 Anthropogenic Heat

Anthropogenic heat could be defined as any source of heat produced by human activities; it could be heat from cars, building facilities, factories or even human themselves. According to Equation 1.1 anthropogenic heat is considered as a primary source of heat gain beside the solar gain in the urban areas. Anthropogenic Heat is considered to be a significant factor because it encompasses the total energy consumption in a city which is directly reflected to the environment. A factor that measures the total energy consumption is called Energy Use Per Capita, which is defined as the amount of total energy consumed in a country divided by its total population. Figure 1.8 shows the energy use per capita of United Arab Emirates and the world, in this case the energy use is measured as kilogram of oil per person. It can be concluded from the graph that each person has released energy equivalent to almost 12000 kg of oil to the environment of UAE in year 2007. Since most of the human activities happen in or around the cities in UAE, it could be concluded that the bulk of this energy has been released directly to the environment of the cities in UAE. Therefore such a major heat release to the city environment is expected to have a significant effect on the increase of temperature within the cities.

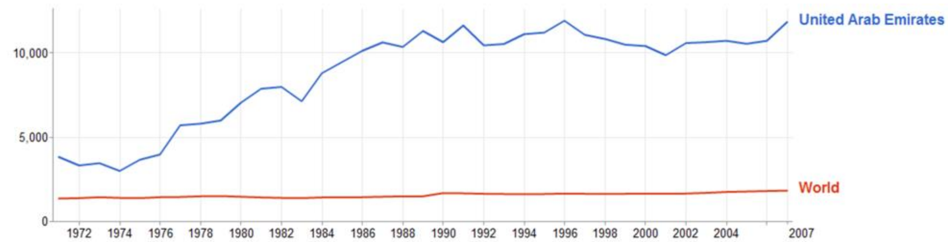


Figure 1.8 Energy Use in Kilograms of oil equivalent, per capita of the World and United Arab Emirates (IEA Statistics, 2007)

1.3.5 Air Pollution

The air pollution can also increase the effect of UHI in the urban areas. As the density of pollutant particles increase in the ambient urban air, they tend to absorb the heat in the atmosphere and cause a rise in temperature of the ambient air. This warm ambient air then emits the heat energy back to the earth and causes a rise in temperature of the urban areas. The pollution is especially effective during the night, in absence of solar energy by increasing the net radiation to the surface of the earth.

1.4 Importance of Urban Heat Island

As mentioned at the beginning of this chapter, 70% of the world population is estimated to live in urban areas by 2050 (United Nations Dept. of Economic and Social Affairs). The fact that urban heat island is a phenomenon that occurs in urban areas (where almost 70% of the world population will be living in future) alerts for a worldwide attention on this challenge. The impacts of urban heat island mainly occur at two levels; first is the energy consumption and second is public health and comfort.

In terms of the energy demands, elevated temperatures in urban areas increase the cooling load of the cities and add pressure to electricity loads during peak hours of demand. This problem specially exists during hot summer weekdays at the afternoon hours when offices, houses and commercial units use air conditioning systems for cooling. Figure 1.9 exhibits the correlation of air temperature with electricity consumption in three

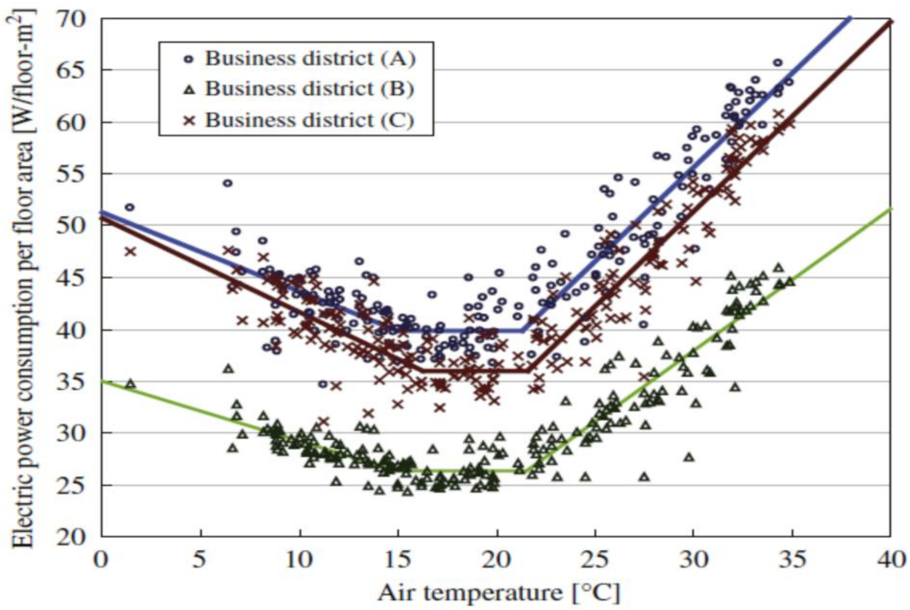


Fig. 4. Air temperature vs. electric power consumption at 14:00 LST during weekdays.

Figure 1.9 Air Temperature vs. electric power consumption at 14:00 in three different business districts in Tokyo,Japan. (Ihara, T. et al , 2008)

different business districts in the city of Tokyo in Japan. The temperature increase has significantly lifted the electricity consumption due to the cooling load in these districts.

During sever heat events which normally happen in summer, urban heat island effect exacerbates the condition by adding extra cooling load to the system to an extent where the electricity demand passes the supply limit of the power plants and power outage occurs. The increase in power demand has a secondary consequence which is the enhancement of consumption of energy resources such as fossil fuels as well as production of greenhouse gases. Currently a lot of power plants in different countries around the world such as UAE, are mainly operating on combustion of fossil fuels; an increase in this process can result in the rise of greenhouse as well as air pollutant gases such as sulfur dioxide, nitrogen oxides particulate matter, carbon monoxide and mercury; this has negative impacts on human health and global warming.

On the other hand, urban heat island affects human health and general comfort level. Negative effects of UHI such as high temperatures during daytime, reduction of nighttime cooling and increased levels of air pollution contribute to diseases such as dehydration, respiratory problems, exhaustion and nervousness, heat related mortality and non fatal heat strokes. Heat islands specially exacerbate the excessive heat exposure diseases in sensitive groups of population such as children, aged adults and people with existing difficulties in health conditions. Figure 1.10 shows the relationship between air temperature and the number of people who were treated for heat related illness in a hospital in Tokyo (Hanaki, 2008); as the maximum daily temperature increased the number of people who were affected by the excess heat increased significantly.

1.5 Measurement Strategies

Now that the causes and impacts of the urban heat island are explained; it is critical to discuss how this phenomenon could be controlled and mitigated. However, before developing any mitigation strategy it is important to measure the urban heat island and locate the hot spots in a city. There are mainly five methods used to measure the heat island effect in a city (Gartland, 2008):

1. Fixed stations: This method is the simplest and most elementary way of measuring urban heat island effect. In this method weather data of different fixed stations, which are located at different parts of a city, are compared in terms of air temperature, solar radiation, relative

humidity, etc. When using fixed stations method, it is crucial to choose the right location for both urban and rural stations; the data collected from these stations should best represent a typical condition of a rural or urban area in order to result in more accurate comparisons.

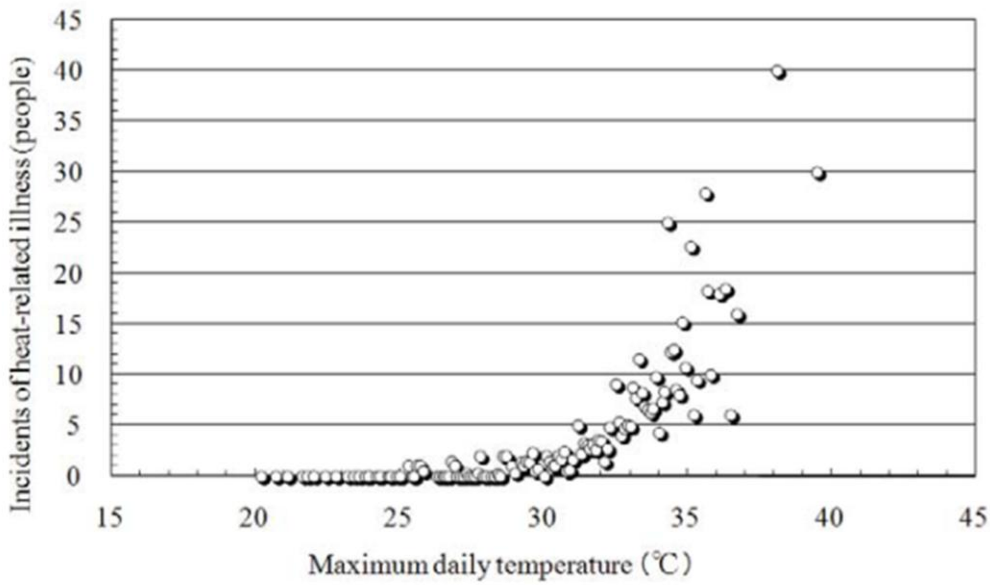


Figure 1.10 Relationship between number of people treated for heat related illness and maximum daily temperatures in Tokyo. (Hanaki,2008)

2. Mobile traverses: This method requires traveling on a chosen path that passes through central urban areas as well as suburban and rural areas. As traveling through the path, the researcher stops at the best representative points and collects certain data such as air temperature and wind speed. Measurements could be taken at any time of the day or night by different traveling means such as a car, by walking or public transport.

3. Remote sensing: This method involves use of specialized equipments, such as airplanes with infrared cameras or satellites, to scan the cities and collect the desired data. These specialized equipments are able to collect data through energy and radiation that is emitted from

different surfaces. Remote sensing allows to collect data over large areas within the same time constrain; however the collected data by remote sensing is only limited to horizontal surfaces and information on vertical surfaces such as walls are missing.

4. Energy balance: This method involves the energy balance equation (equation 1.1); as discussed earlier the energy that is received by surfaces through the sun and anthropogenic sources is reflected back to the environment through convection, absorption or evaporation. Energy balance experiments basically measure and evaluate the energy in and out of different surfaces located at different parts of the urban areas.

5. Vertical sensing: The temperature within the environment of a city varies at different altitudes; in order to measure the temperatures difference in a city vertically, specialized equipments are used to collect data from both canopy and boundary layer. This method is specifically useful to measure the effect of heat islands on thermal inversions and concentrations of certain gases in the boundary layer.

1.6 Mitigation Strategies

Like any other environmental problem, urban heat islands could be controlled and mitigated through several strategies. The mitigation strategies of UHI are directly related to the causes of this phenomenon and they mainly deal with alteration of building materials and increasing evaporation by adding greenery. These mitigation strategies could be categorized under three main groups:

- Cool roofs and pavements
- Green roofs
- Urban Vegetation and greenery

All these strategies aim to focus on controlling the absorption of the heat and its release to the environment in order to establish a balance between heating and cooling of the urban fabric.

1.6.1 Cool Roofs and Pavements

This strategy is used to address the problem of heat absorption which is caused by traditional building materials in different cities. It requires the replacement of traditional roofing or pavement materials by so called “cool” materials. There are two properties that help cool materials remain in low temperatures even during the hottest summer days; high solar reflectance or albedo and high thermal Emittance. High solar reflectance refers to the high ability of the material to reflect the suns energy away compared to traditional materials. On the other hand, high thermal Emittance enables the material to radiate the collected heat away from its depth and remain cool.

In terms of the roofing cool materials different types are used for flat or inclined roofs due to difference in roofing composition. Flat roofs usually use coatings of cool materials for improvement of existing roofs or prefabricated panels of cool materials for construction of new roofs. Some of these materials include PVC (polyvinyl chloride), CSPE (chlorosulfonated poly-ethylene), EPDM (ethylene propylenediene monomer) and etc. on the other hand inclined roofs use different cool materials in form of tiles and painted metal roofing. In terms of pavements there are mainly two most common traditional materials used to cover the pavements; concrete and asphalt. Both of these materials absorb and restore heat due to their thermal properties and dark color. There are basically two ways to create cool pavements; first is by adding light colors to their surface and increase the solar reflectance and second is by making them permeable surfaces that are able to absorb water during rainy hours and use the absorbed water to release heat in hot hours of a day.

Many studies have focused on the important effect of cool materials and reduction of the surface temperatures in urban environments. Figure 1.11 shows the difference between the surface temperatures of different colored concrete materials in July; there is a significant temperature different of 20 ^{0}C between the black and off white concrete. Therefore cool materials are one of the most important mitigation strategies that could be used to reduce the effect of urban heat island.

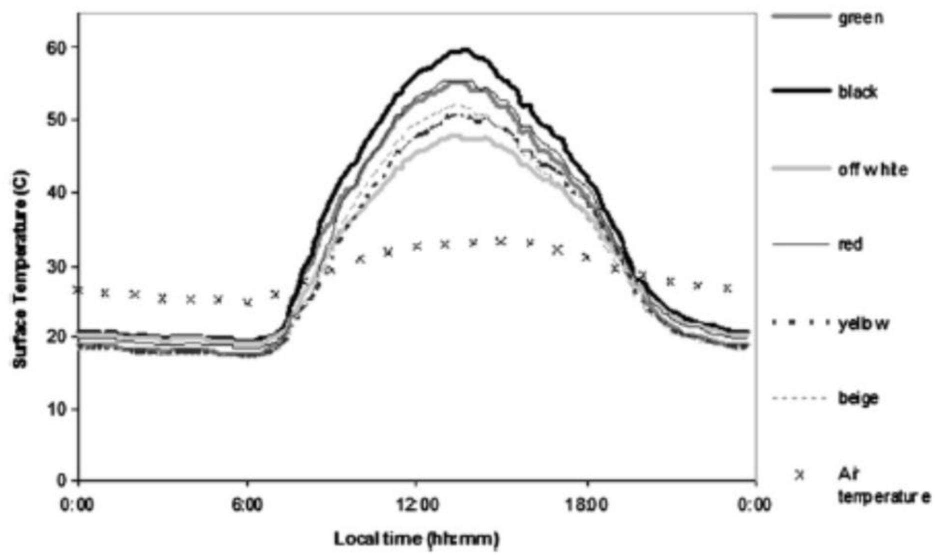


Fig. 4. 24h distribution of the mean hourly surface temperatures of the tested samples and air temperature during the experimental period (July 2008).

Figure 1.11 Distribution of the mean hourly surface temperatures of the tested materials and air temperature during July. (Synnefa,2011)

1.6.2 Green Roofs + Urban Vegetation and Greenery

A roof surface has the most sun exposure and heat absorption compared to other surfaces in every building; this is due to its horizontal orientation, which is perpendicular to the sunrays. In fact roof surfaces are one of the most important contributors of urban heat island in the cities and therefore a considerable amount of research and analysis has been conducted regarding roof issues. Besides cool roofing, green roofing is another technique, which has been applied as an effective mitigation strategy; green roof can be defined as adding a layer of any type of vegetation to the roof in order to minimize the amount of heat-gain both internally and externally through the rooftop. Green roofs contribute to the reduction of heat gain utilizing two phenomena; first is shading and second is a process known as evapotranspiration. Vegetation layer adds shading to the roof membrane and blocks the sun rays to penetrate through and reach the roof top; in return the foliage and leaves of trees or other types of greenery either absorb the light for photosynthesis or reflect and emit it back to the environment. Green roofs also reduce heat gain through the process of evapotranspiration. On one hand, plants absorb water from the ground through their roofs and circulate this water to their leaves and other parts in a process called transpiration. On the other hand, plants convert the existing water in their leaves to gas by evaporation, which happens during photosynthesis. Both transpiration and evaporation are referred to evapotranspiration, which results in cooling the surrounding air by absorbing heat for evaporation. There are two main types of green roofs; extensive and intensive green roofs. Extensive green roofs normally are a thin green rug layer requiring minimum maintenance; intensive roofs however consist of big plants such as trees and shrubs and require more maintenance.

The other important mitigation strategy to urban heat island effect is to increase the amount of vegetation in the urban fabric. As explained earlier, trees and greenery contribute to the cooling of the urban environment through shading and evapotranspiration. The leaves and foliage of trees shade the underneath surfaces such as pavements and streets and block the penetration of sun rays while evapotranspiration absorbs heat from the surrounding environment and adds water vapor to the air. There are several factors that contribute to the effectiveness of greenery in reduction of heat in urban areas, evapotranspiration rate which depends on the type of greenery; location of the vegetation and greenery in relation to the build environment;

density and form of the greenery; and water use. Vegetation and greenery could be added in the form of large-scale landscape such as parks and recreational areas or small-scale landscapes such as rows of trees and grass within the urban fabric.

There are a lot of direct and indirect benefits associated with green roofs and vegetation in the urban environments; some of these benefits are reduction of energy use, reduction of air pollution, reduction of greenhouse gas emissions as well as improvement of health and human comfort level. One of the main benefits of the green roofs and vegetation is reduction of surface and ambient air temperatures; this effect is the main focus of this research and would be discussed in detail next chapter.

CHAPTER 2

Literature Review and Research Objectives

2.1 Introduction

As mentioned in the previous chapter, research on urban heat island dates back to 1818 when scientists started to notice the effect of excess heating in urban areas. Since then research and analysis on urban heat island has expanded tremendously; currently UHI is considered to be a wide field of study involving civil and environmental engineers as well as architects and urban planners. The body of research on urban heat island could be divided into three categories; (1) Studies on causes of urban heat island in different cities, (2) Studies on measurement and modeling of the extent of urban heat island in different cities, (3) Studies on application, analysis and the effectiveness of mitigation strategies. Each of these categories encompasses narrower range of topics that have been studied in the 200 year history of urban heat island. In recent years, due to the raised concern and awareness on the impacts of urban heat islands, a large part of the research has focused on the mitigation strategies and their application in different situations. This category of research also divides into narrower topics that cover specific mitigation strategies such as cool materials (roof and pavement), green roofs and urban greenery.

2.2 Cool Materials

The topic of cool materials could focus on study of different types of materials or study of different types of coatings, which could be applied on conventional materials. For instance, Wanphen and Nagano (2009) have focused on the effect of porosity in different materials on reduction of heat by utilizing their evaporation and moisture absorption capabilities. Analysis of four different types of porous materials that could be used as a roofing material suggested that siliceous shale is capable of reducing the surface temperature of a rooftop by up to 6.8-8.6 °C depending on the diameter of its pebbles. Another study investigated the effect of reflective coatings of materials on reduction of surface temperature as well as their effect on mitigation of urban heat island (Synnefa, et al., 2008). Fourteen different coatings available in the international market were selected and applied on different parts of buildings for a period of observational experiment. The results yielded that the use of appropriate coatings can significantly reduce surface temperatures; for example white coating on a concrete tile reduced its surface temperature by 4 °C during the day and 2 °C during the night. Different types of cool color coatings were developed and tested for the amount of solar reflectance and ability of surface temperature reduction by Santamouris, et al. (2007). A cool colored coating and a standard colored coating exhibited a difference of 22 units in solar reflectance which resulted in temperature difference of 10.2 °C for summer conditions. Figure 2.1 graphs the relationship between solar reflectance and maximum surface temperature for different materials; low values of solar reflectance can result in extremely hot surface temperatures up to 75 °C while high values of solar reflectance significantly reduce the surface temperatures.

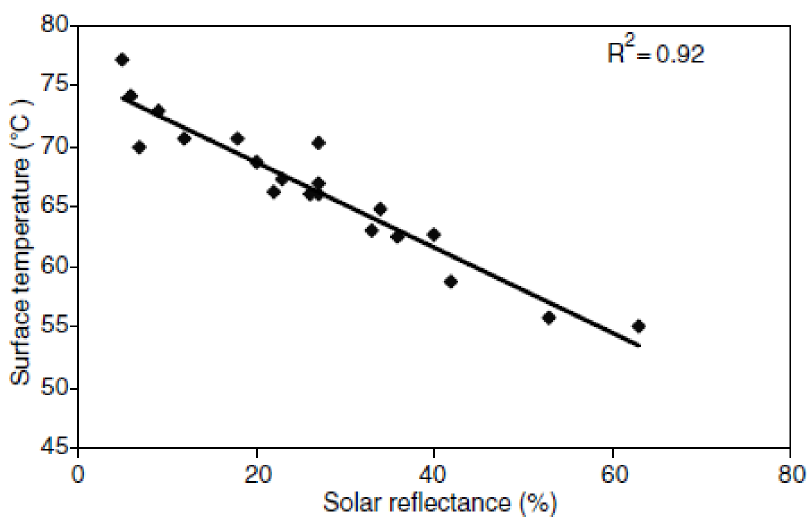


Figure 2.1 The correlation between maximum daily surface temperature and the solar reflectance of different materials. (Santamouris, et al., 2007)

Since this research focuses on the effect of greenery as a mitigation strategy on reduction of urban heat island, this chapter reviews the body of research and analysis on this topic in detail. For the purpose of clarity, the reviewed research papers have been categorized based on form and scale of the greenery as applied within the urban fabric into following categories; each of these categories is discussed in the following sections.

- Studies on the mitigation effects of Small scale application of greenery
- Studies on the mitigation effects of Large scale application of greenery
- Studies on the mitigation effects of Green roofs
- Studies on the mitigation effects of Vertical greenery

2.3 Studies on the Mitigation Effects of Small Scale Application of Greenery

The body of research in this area focuses on different specific aspects of application of small scale greenery within the urban fabric such as microclimatic effect, green cover, density and configuration and etc. However some studies focus on the overall relationship between green land cover and surface temperature. Avissar (1994) studied the relationship between vegetation and land atmospheric interactions in the urban areas; based on this study these interactions involve complex mesoscale and turbulent processes depending on percentage of vegetation cover in the urban area and type of rural surrounding. On the other hand, Zhanga, et al. (2010) studied the relationship between surface temperature and NDVI (Normalized Difference Vegetation Index, a numerical indicator used to study vegetation cover on the land from satellite data) in the city of Beijing, China. In this study it was concluded that the distribution of vegetation cover is low in center and high in the edges of the study area while the distribution of the temperature was opposite to vegetation cover, low at the edges and high in center; this observation revealed the significant negative relationship between vegetation cover and surface temperature. The strengths of this correlation is affected by two factors of complexity of the underlying land structure (the more complex land structure such as the city center leads to stronger correlation between temperature and NDVI) as well as weather conditions. Also, Zhoua, et al. (2011) studied the effect of composition and configuration of land cover on land surface temperature; this study revealed that composition of land cover feature is more important than configuration in determining the magnitude of LST. In this regard, percent cover of building most significantly affected the increase of LST, while percent cover of woody vegetation has the most significant effect on decreasing LST. In terms of configuration, an increase in complexity, edge density and variability of woody and herbaceous vegetation (Zhoua, et al., 2011) could significantly decrease the land surface temperature.

The microclimatic role of small scale urban greenery on thermal comfort of was done by Georgi and Dimitriou (2010). In this research, certain study areas were chosen based on several criteria such as frequency of tree species, good fit in urban environment and vegetable factor; then certain parameters that contribute to the thermal comfort of the urban climates were analyzed and measured such as tree species, air temperature, relative humidity, wind speed and discomfort index. The results of data analysis showed that temperatures of selected green areas were lower than sunlit pavements in all cases with a mean reduction of 3.1 ^{0}C. On the other hand, the temperature and discomfort index values differed for various kinds of species (Georgi and Dimitriou, 2010).

The highest values were reported under drought tolerant evergreen Mediterranean types of trees that provide a low relative humidity air; however the lowest temperatures were reported under tropical types that provide higher relative humidity air by evapotranspiration. Figure 2.2 shows the relationship of evaporation rate of a tree with the temperature that is developed under it; as the evaporation rate increases the developed temperature decreases. The DI (discomfort index) and relative humidity have reverse relationship meaning the higher the RH the lower the DI. Therefore it is encouraged to plant trees that produce higher relative humidity such as tropical trees for dry and hot summers (Georgi and Dimitriou, 2010). The evaluation of these green areas and their positive effect on thermal comfort of the urban area signifies the necessity to develop such areas more within the cities.

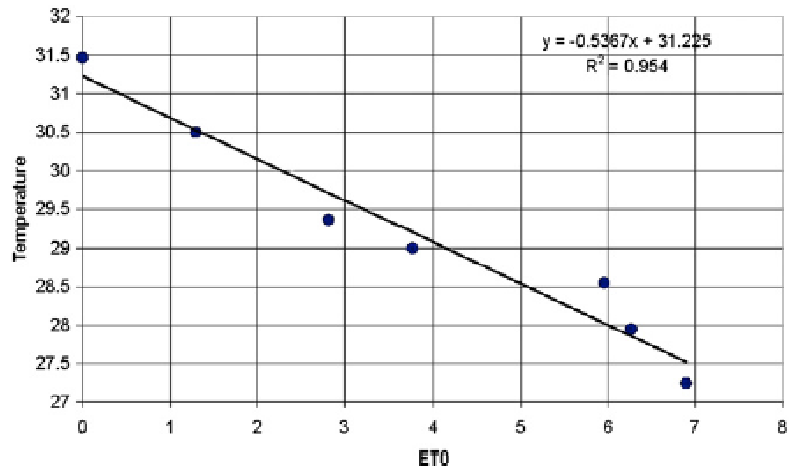


Figure 2.2 The comparison of evaporation rate with developed temperature under each tree species (Georgi and Dimitriou,2010)

Some researchers have focused on the role of trees specifically, and their effect on reducing the temperature within the urban areas. Quattrochi (1998) believes that the effectiveness of trees in absorption of solar radiation and reduction of urban temperature depends on three properties; foliage density, leaf shape and evapotranspiration. The shape of the individual leaves help to scatter the solar radiation and avoid heat storage within the canopy; on the other the hand, the shape and density of the canopy itself absorbs the heat and prevents it from reaching to the underneath surfaces. However, Quattrochi (1998) believes that the most important thermal control that a tree contributes to its surrounding environment is through evapotranspiration; depending upon the moisture available a single tree may transpire 400 liters of water in one day. Therefore this evaporative process greatly reduces the amount of stored solar energy and cools down the environment. Shashua-Bar and Hoffman (2003) conducted a quantitative analysis for predicting temperature reductions within the urban areas caused only by trees. In this study the Green CTTC model (a model developed by Shashua-Bar and

Hoffman (2003)) was used to simulate diurnal temperature changes for four study points, with and without trees. The results of this simulation were then compared to empirical study of the selected points for validation. The results of both studies revealed that the cooling effect of the trees depended on tree density and cluster geometry of the surrounding urban area. Also the average cooling effect of trees in streets of Tel-Aviv was 2.5 K while the cooling effects of the trees in courtyard were found to be at a range of 2.5–3.1 K (Shashua-Bar and Hoffman,2003). The combined effect of trees, surface albedo and cluster deepening resulted in 4.5K reduction in at midday in summer (July–August), a cooling effect which is about 50% of the air temperature rise from sunrise to noon hours. Figure 2.3 shows the cooling effect through simulated and measured in situ values of diurnal air temperature in streets and courtyards of Tel-Aviv with and without trees.

Giridharan, et al. (2007) focused on the impacts of onsite variables such as sky view factor, altitude, shrub cover and tree cover on the influence of vegetation in mitigating the UHI effect. The study showed that tree cover dominated locations are cooler by 0.5-1 ^{0}C compared to shrub cover dominated locations during peak summer clear sky days. Also 40% of vegetation covers, in a low rise and low density urban setting could lower the UHI by more than 1.0 ^{0}C; however the same amount of greenery in a high rise and high density setting results in temperature reductions of less than 1.0 ^{0}C. This result approves the observation of Zhanga**, et al.** (2010) regarding the correlation of the complexity of the urban fabric with the effect of the vegetation on lowering UHI. Giridharan, et al. (2007) also revealed that on site factors such as sky view factor and altitude counteract the effect of vegetation on lowering UHI in high density and high rise urban settings. The study shows that for the sky view factor of 0.25–0.45, vegetation cover of less than 20% will not help to reduce UHI in high rise and high density urban fabric; on the other hand, for the sky view factor of 0.1-0.25, vegetation cover

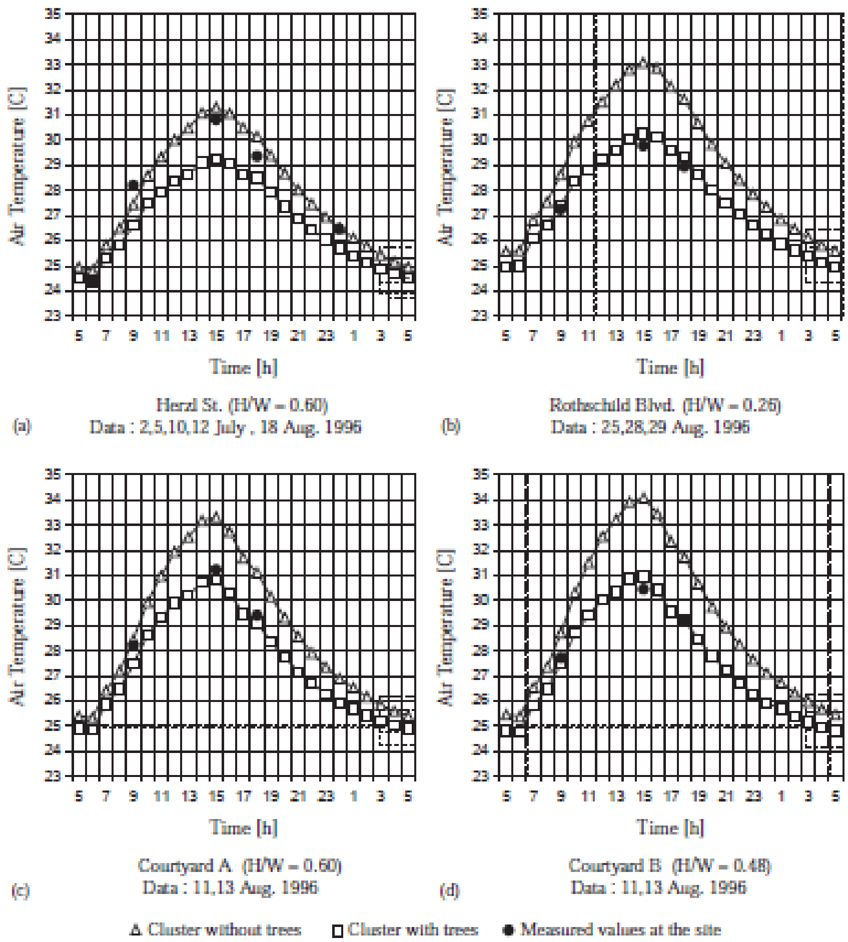


Figure 2.3 Simulated and measured values of diurnal air temperature for streets and courtyards of Tel-Aviv. (Shashua-Bar and Hoffman, 2003)

of less than 20% could help the reduction of UHI in low density and low rise urban fabric. Therefore this study signifies that introduction of vegetation within an urban setting should be done by accurate consideration of other factors such as sky view factor and altitude within the urban areas.

Another study focused on investigating the mitigation effect of grass covered parking lots on urban heat island (Takebayashi and Moriyama, 2009). This study was done through field experiment on a parking lot located in a residential area in the city of Kobe in Japan; different types of materials such as wood, concrete and blocks were used in combination with grass to test different scenarios. For evaluation of mitigation effect, surface temperature and underground temperature were measured using thermocouples; in order to monitor the weather conditions, solar radiation and infrared radiation were also recorded on the roof of the nearby university. The results of this study confirmed the reduction of surface temperature of parking lots by converting to grass cover; however the mean surface temperature varied greatly depending on types of materials that were used in combination with grass (figure 2.4).

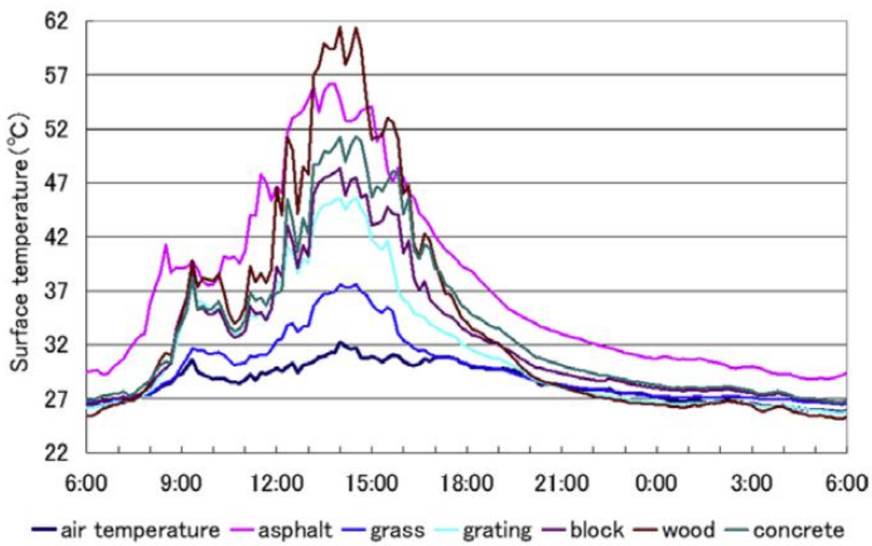


Figure 2.4 Observation results of surface temperature for the typical parking space on July 30 and 31, 2005. (Takebayashi and Moriyama, 2009)

Also the estimation result on air temperature changes in case of converting to grass parking lots in a whole urban area revealed that the air temperature would decrease by almost 0.1 k only; this is due to the limited number of parking lots in the city of Kobe. Therefore the strategy of converting to grass covered parking lots should be used along with other mitigation strategies to yield significant results.

In another attempt to study the effect of small scale greenery, Wong, et al. (2007) studied the effect of a green cluster on microclimate and energy savings on the campus of the National University of Singapore as a result of improving the green area. Based on satellite images, the NUS campus was divided into 3 zones of dense greenery, medium greenery and sparse greenery; in each of these zones temperature and relative humidity were measured on 10-24 of September. Then Envi-met software was used to simulate three different scenarios beside the current condition of these green areas; first replacing dense trees by buildings, second removing all greenery, third replacing grass land by more trees. Also, the engineering building was selected to conduct a TAS simulation for determining cooling energy consumption for different ambient temperatures at different locations. The ENVI-MET simulation revealed that the removal of greenery results in higher ambient air temperature with no cooling effect on surrounding buildings.

Also replacing the dense forest by buildings resulted in higher temperatures compared to the current condition however this situation has lower hot spots; on the other hand adding more greenery to the current condition has increased the cooling effect significantly; Figure 2.5 shows the results of ambient air temperature for all four scenarios during day time. Also the results reveal that a denser building fabric leads in lower cooling effect and this fact is especially evident during nighttime. According to TAS simulations, the ambient air temperature had a significant effect on cooling load as a 5.4% difference was seen between hottest and coolest ambient temperatures including internal heat load.

2.4 Studies on the Mitigation Effects of Large Scale Application of Greenery

Some of the studies on mitigation effect of greenery focus on the impact of large scale greenery, such as urban parks and urban forests on UHI. In this regard some researchers investigated the role of urban forests compared to other land use on mitigation UHI. Stabler, et al. (2005) studied the seasonal relationships of microclimate, urban plant cover and land use in Phoenix, USA; a normalized differential vegetation index (NDVI) map produced from a Land Sat thematic mapper image of the Phoenix, was used to explore the spatial patterns of microclimate conditions, land use and urban greenery density. These parameters were analyzed in four study areas ranging from residential, commercial and rural areas along the Phoenix metropolitan; this study confirmed that land use affected the microclimate in all four areas with more pronounced effects on early mornings. In terms of the relationship of microclimate and NDVI, the most prominent correlation was recorded on the area which crossed the urban core along its southern extent and a mature dense vegetated area to its north.; it was found that there is a strong negative correlation between NDVI and surface temperature in this area, meaning the lower the NDVI the higher the surface temperature. However this study found that using NDVI as the only parameter to determine the microclimate could underestimate the temperatures; therefore the

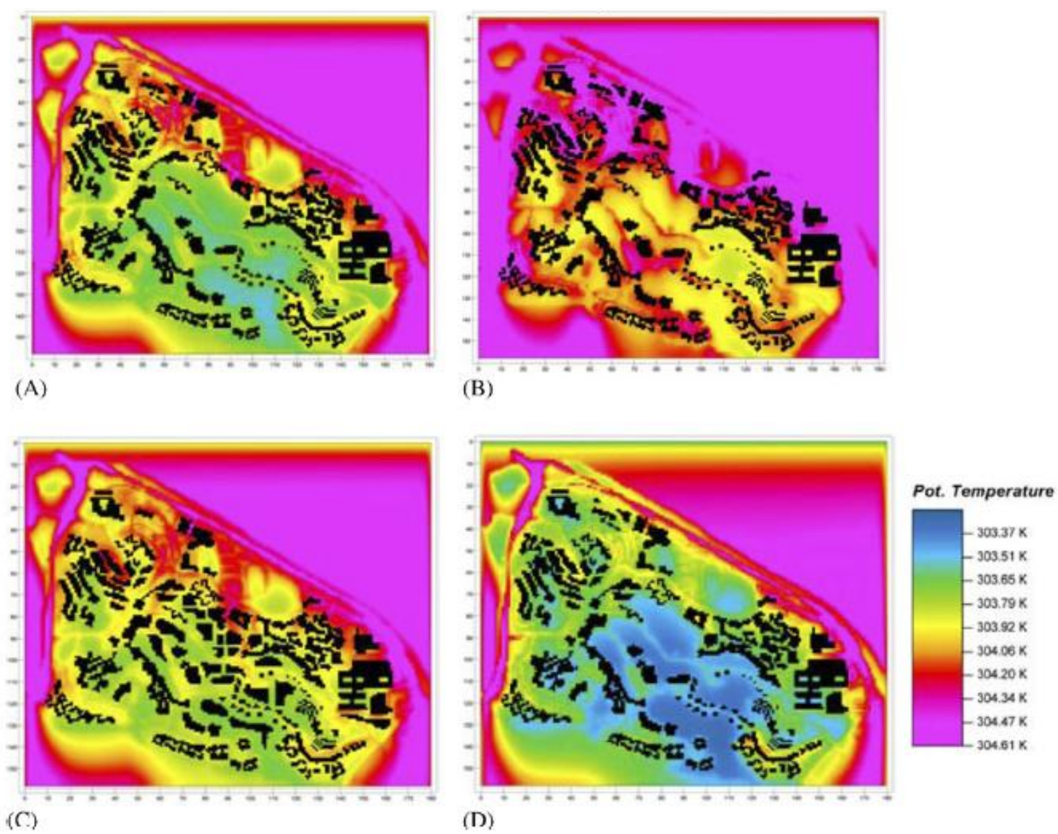


Figure 2.5 Predicted daytime ambient temperature site plan: (A) current condition; (B) without greenery; (C) replacing forest with buildings; (D) introducing denser greenery. (Wong, et al., 2007)

microclimates at Phoenix are more likely an interaction of urban forest with no vegetated surfaces such as parking lots and buildings; this interaction is related to the degree of urbanization near the urban core and density of urban forests (Stabler, et al., 2005).

On the other hand, some of the studies in this area focus on characteristics of urban parks and forests. Caoa , et al (2010) studied the role of urban parks characteristics such as size, shape and land use in the amount of Park Cooling Intensity; a parameter that measures the ability of a park to create a cooler environment within the urban fabric (Figure 2.5). In this study Remote sensing images (ASTER LST and IKONOS) were used to study park cooling intensity or PCI which is the temperature difference between the inside and outside of a park. The results of this study showed that large parks had significantly lower temperatures than the rest of the city during summer and spring however this temperature difference was lower during autumn; therefore with increasing the park size, the PCI factor increased considerably for summer and spring. However the results also revealed that the relationship between PCI and size is non -linear and complex and it can only explain 60% of PCI phenomena. In terms of land use and park shape, the results show that PCI is negatively affected by grass and positively affected by shrub and trees in both spring and summer. This means that shrubs and trees have equal contribution in formation of PCI effect while the negative effect of the grass cover was due to its unfavorable condition of growth resulting in vast areas of bare soil. It was also concluded that the compactness of the park has positive effect on PCI while irregular, complex and linear shaped parks contribute less in PCI (Caoa , et al., 2010). Chang, et al. (2007) also studied the role of park characteristics on their cooling effect as well as verifying whether this cooling effect is different among various parks of Taipei city. 61 parks of different size in Taipei were surveyed and analyzed in these studies; the results confirmed the “cool island effect” of urban parks in this city as recorded cool island intensity of 0.81K for summer days and 0.57K for winter days. It was confirmed that the parks have higher cooling intensity in summer compared to winter and also this intensity is higher at noon time compared to night. In terms of the coverage characteristics, trees and pavements affect the park temperatures the most, as trees benefit the cool island intensity and pavements counteract the park's cooling intensity. Due to the dominant pavement coverage, one fifth of the parks (14 out of 61) were on average 0.42K warmer than their surrounding areas. Regarding the park size, the larger parks showcased stronger cooling intensities compared to smaller parks; in particular, parks larger than 3 ha. were found to be more consistently cooler than their surroundings at noon in summer, whereas smaller parks varied widely in their cool island intensity (Chang, et al., 2007).

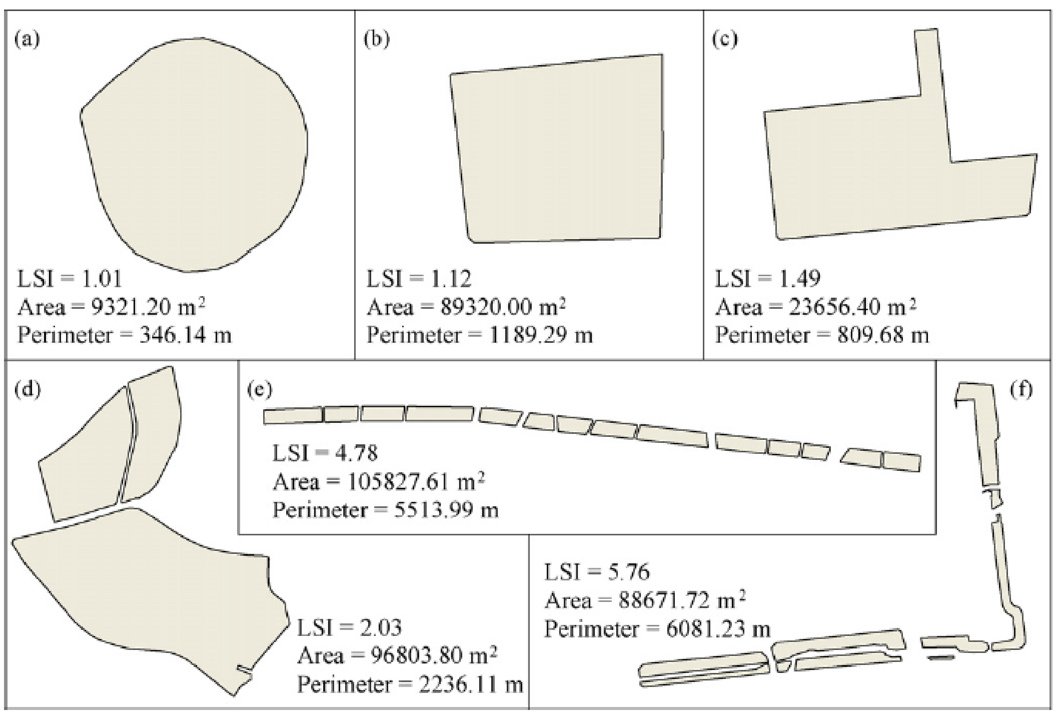


Figure 2.6 Different park characteristics: (a) near circle, (b) Square, (c) semi-square, (d) irregular polygon, (e) roadside belt-shape, (f) irregular belt-shape. (Caoa , et al., 2010)

Gomez (1998) attempted to outline the role of large urban green areas on distribution and pattern of urban temperatures. He used 22 observation points that best represented the diversity of urban density as well as situation of urban parks of certain size; in this observation the cooling effect of the green areas was confirmed and the mean temperature difference of 2.5°C was recorded at the selected urban parks. Won and Yu (2005) also studied the cooling effect of large green areas at macro level in Singapore; in this study mobile survey was conducted to map out the temperature and humidity profiles at various regions of urban core and urban forests in Singapore. The collected data from central business district and a green recreational area at the northwest of Singapore were compared to determine any relationship between high density plant cover and temperature reduction. Table 2.1 shows the results of the data comparison for these two areas; according to this table the mean temperature of the well planted area is 3.07 ^{0}C lower than the building dominated area, this comparison confirms the cooling effect of urban parks at macro level in the city of Singapore.

Table 2.1 Statistical comparison of northwest open area and CBD area in Singapore. (Won and Yu, 2005)

	Sample no.	Mean	Max	Min	Standard deviation	Standard error
Open area/recreation	10	25.01	25.95	24.30	0.51	0.16
CBD area	12	28.08	28.31	27.70	0.22	0.06

Hamada and Ohta (2010) focused on measurements of air temperature in green urban areas (that include forests and grasslands) and their surroundings to clarify the characteristics of urban greenery and its cooling effect. Both diurnal and seasonal variations were measured to compose a range of cool island effect from green area to urban area throughout the year. The study was carried out on a 147 ha Urban park in the city of Nagoya, Japan. 24 sites were selected in and around the park and temperatures and humidity were measured on each site from August 2006 to March 2008; in order to determine the daily and seasonal temperature variations between urban park and surrounding urban areas, the temperature difference between each site and a base site with no surrounding greenery was measured. The results of data analysis revealed that there was a clear daily variation of temperature difference among different sites; the largest temperature difference was 1.9 C at 16:00 in July 2007. In terms of seasonal changes, the temperature differences were smaller in winter and as the days approached to warmer months, the temperature difference increased. Also it was revealed that air temperature varied according to the profile of the greenery; meaning as the height increased the temperature difference increased as well due to larger areas of leafs on top of trees compared to the bottom. In terms of correlation of distance from the park and cooling effect it was concluded that the cooling effect reached to 300-500 m from the park during the summer daytime and 200-300m during nighttime. The cooling effects of large urban parks on their surrounding areas were confirmed in this study; however the extent of this effect might vary based on geometry and anthropogenic activities in the surrounding areas.

2.5 Studies on the Mitigation Effects of Green roofs

Green roofs are another area of research focus with regard to mitigation of urban heat island. Chen, et al. (2002) explored the direct and indirect impact of roof gardens on the environment of the tropical city of Singapore. The study was carried out on the rooftop of a low rise building which features grass, shrubs, trees and pavements surfaces. In terms of direct impacts, the results of the field measurement revealed that green roofs significantly reduce the roof surface temperature; figure 2.6 shows a comparison of surface temperature of different species of plants, bare soil and concrete roof. According to the figure, the surface temperature of roof surface without plants could reach up to 57 ^{0}C during afternoon; bare soil surface temperature reaches 42 ^{0}C which is lower than concrete; however, various species of plants result into significantly lower temperatures than both bare soil and concrete surface.

The results also showed that the cooling effect of the plant depends on leaf Area Index or LAI since higher temperatures were recorded under plants with sparse foliage while lower temperatures were recorded under plants with dense foliage. Indirect impacts of the roof garden refer to their thermal effects on surrounding environment; in order to determine these impacts Chen et al. (2002) measured the ambient air temperature at different heights of 300,600 and 1000 mm above the hard surface. At lower heights of 300 and 600 mm ambient temperature difference between vegetation and hard surface were recorded to be high while temperature difference at 1m high was recorded to be lower. The most temperature difference was 4.2 C which was recorded at 300mm height above the surface. Susca, et al. (2011) studied the long-term energy savings of white roofs and green roofs which is considered as another indirect impact of temperature reduction by green roofs. Susca, et al. (2011) related the reduction in energy use of these two types of roofs, to their surface albedo which causes lower surface temperatures. Figure 2.7 shows the comparison of the energy savings of both roof types against black roof for two scenarios (Scenario I and Scenario II refer to different locations of green roofs with different climatic conditions) application of green roof on different

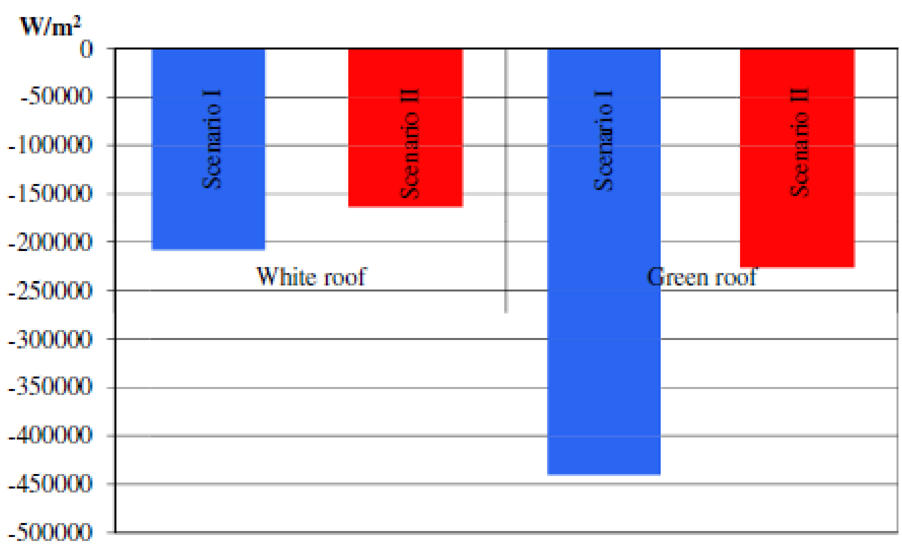


Figure 2.7 Saved energy for green and white roof compared to black roof (Scenario I and Scenario II refer to different locations of green roofs with different climatic conditions) . (Susca, et al., 2011)

over a time span of 50 years; according to this figure the application of green roof is the most favorable option as it results in energy savings of 40%-110% compared to white roof.

Fioretti, et al. (2010) also studied the effect of greenery on reduction of roof heat in the city of Marche in Italy. In this study the reduction of solar radiation on the green roof of a building was analyzed by comparing the global solar radiation and the monitored solar radiation measure above and below the foliage of greenery; this analysis showed that the irradiance under and above the foliage of a green roof was reduced by almost 80% during specific days chosen as representative of the respective month in the hot season. This study also confirmed the reduction of surface temperature of the green roof due to the foliage shading and evapotranspiration. Table 2.2 shows the monthly average temperatures of a typical reference roof as well as temperatures under the foliage and soil; these data also confirm the tremendous effect of green roofs on the reduction of surface temperature in agreement with Chen, et al. (2002).

Table 2.2 Monthly average temperature at the external surface of the reference roof,under the soil,under the foliage and average drybulb temperature.(Fioretti, et al.,2010)

Month	External surface temperature (reference roof) [°C]	Temperature under the soil [°C]	Temperature under foliage [°C]	Dry bulb temperature [°C]
June	28.37	22.54	22.02	22.98
July	30.10	25.11	24.99	25.82
August	31.72	24.46	24.89	25.65
September	23.23	20.78	18.05	18.81

Wong and Jusuf (2008) studied the effect of implementing green roof on reduction of ambient air temperature in National University of Singapore. This study was the continuation of a previous study by the same team of researchers on the effect of greenery on microclimate of the National University of Singapore campus (Wong, et al., 2007). At first, the old and new buildings on the campus were identified and quantified to study the potential of adding green roof to them. Then three different scenarios were designed to analyze the potential rooftop greenery on new and old buildings on campus; these scenarios were 25%, 50% and 75% of building's rooftop available for greenery. The results of this analysis showed that For 25% rooftop greenery application, the increase of green rate can be up to 3.41%, while for 50% rooftop greenery is up to 6.81% and for 75% rooftop greenery can be as high as 10.22 % (Wong and Jusuf,2008); based on the green rate increase, buildings were prioritized for adding roof garden. After this analysis the effect of green roof on ambient air temperature around the first priority building was simulated in Envi-met software. Figure 2.8 shows the night time

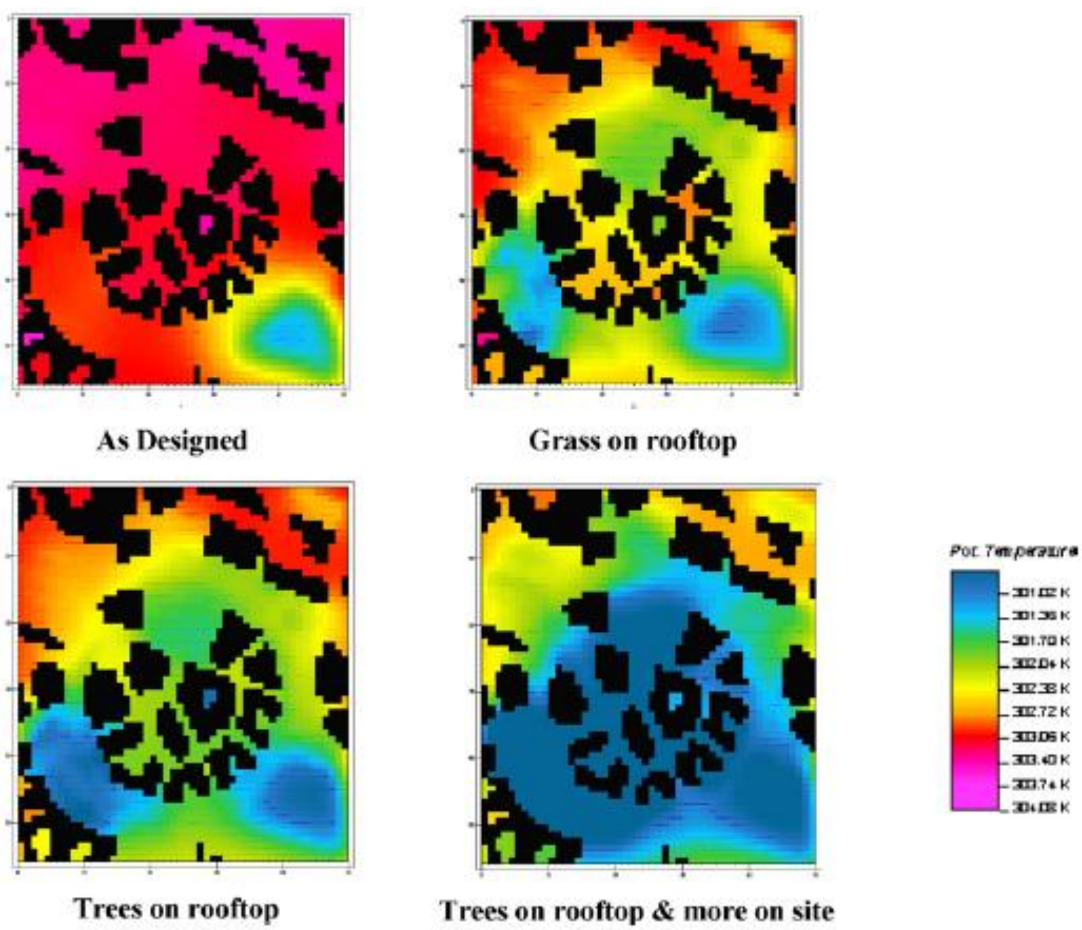


Figure 2.8 Comparison of the night time ambient air temperature for 4 scenarios of roof cover. (Wong and Jusuf,2008)

ambient temperatures of 4 different scenarios of roof top cover for the engineering buildings on NUS campus. The two scenarios of grass and trees roof cover have both resulted in significantly cooler conditions; however this effect is considerably increased when roof garden strategy is combined with improving the amount of greenery on site. Even though the positive effect of roof garden on reduction of ambient temperature is approved in this study, it is important to analyze and calculate the right type and amount of green roof that could result in the best condition for different locations.

Alexandri and Jones (2008) developed a two-dimentional predictive micro scale model to study the effect of application of green envelope on buildings on reduction of heat at the canyon and rooftop level in nine different cities around the world. The maximum air temperature reduction 1m above the roof surface achieved by green roofs in all locations ranges from 26 ^{0}C for Riyadh to 15.5 ^{0}C for London and daytime average temperatures from 12.8 ^{0}C for Riyadh to 5.8 ^{0}C for Moscow (Alexandri and Jones, 2008). In terms of the thermal comfort green roof does not have significant effect for cities such as Moscow with mild summers; however for a city such as Riyadh thermal comfort variations are more dramatic; according to figure 2.9 the thermal comfort reaches to very hot level for the bare concrete roof (no green), while when covered with greenery (PET.rf [gra]), the heat reaches to “warm” level for around 5 hours in a day and falls to slightly warm and comfortable zone for most of the day. A comparison of the effect of green roofs on different cities around the world in this study (Alexandri and Jones, 2008) revealed that application of green roofs could have larger cooling effect in dry hot climates such as Riyadh and humid climates such as Hong Kong which could reach up to 8.4 ^{0}C maximum temperature difference.

2.6 Studies on the mitigation Effects of Vertical Greenery

Tan, et al. (2009) studied the effect of vertical greenery on reduction of urban heat island as part of a research on energy simulation of vertical greenery

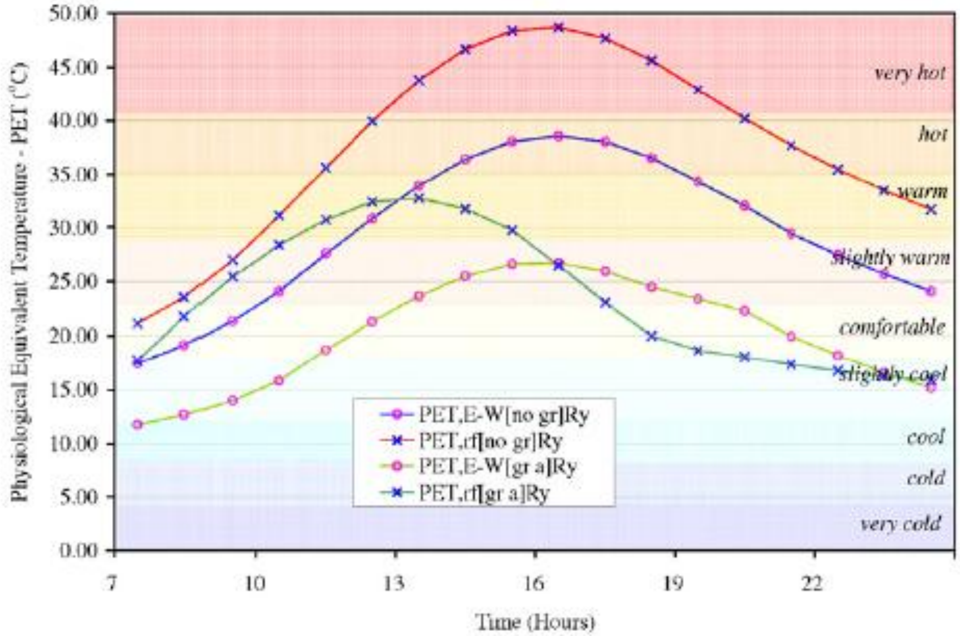


Figure 2.9 PET for the no-green [no gr], green-all [gr-a] and roof green (rf) for Riyadh. (Alexandri and Jones, 2008)

systems. In this study an air temperature prediction model called STEVE (Screening Tool for Estate Environment Evaluation) is used to determine the ambient air temperature difference for two scenarios. In scenario 1A all the vertical greenery is removed from the estate implying a 0 green plot ratio; in scenario 1B vertical greenery is applied on 100% of the available wall surfaces. Scenarios 2B to 2E are designed to predict the air temperature for vertical greenery coverage of 25%, 50%, 75%and 100%. Table 2.3 shows the minimum and average estate air temperatures for all the designed scenarios. Comparison of the scenario 1A and 1B shows reduction of almost 1 ^{0}C in minimum ambient temperature by adding vertical greenery system; however in terms of the average temperature in all scenarios, the reduction is negligible (compared to minimum temperature). There are a lot of factors that play a part in effect of vertical greenery on microclimates; for example, Alexandri and Jones (2008) studied the impact of the characteristics of vertical greenery and street canyon on the microclimate in nine different cities around the world.

Table 2.3 Minimum and average estate temperature for designed scenarios. (Tan, et al., 2009)

Scenarios	Estate air temperature (°C)			
	Minimum		Average	
	Lowest	Highest	Lowest	Highest
1A	25.33	26.22	28.03	28.91
1B	24.53	26.22	27.73	28.86
2A	24.84	26.16	27.98	28.88
2B	24.81	26.16	27.91	28.87
2C	24.78	26.16	27.83	28.86
2D	24.73	26.16	27.76	28.84
2E	24.43	26.16	27.68	28.84
2F	–	–	27.90	28.89

In terms of the orientation, the study showed that there is no significant relationship between orientation of the street canyon and the cooling effect of the vertical greenery despite the fact that orientation plays an important role on distribution of temperature in and around the canyon. However the amount of vegetation placed on the building envelope plays a more important role on the cooling effect; for example using green roof in combination with green walls yields more reduction in temperature of the canyon. Also it was concluded that wider canyons diminish the cooling effects of vertical greenery due to the increased amount of solar radiation received by surfaces; for example in Riyadh, the cooling effects of a wide canyon was 1.2^{0}C for the daytime average temprature while in a narrow canyon this temperature difference reached to 6.3 ^{0}C . Also the thermal comfort inside the canyon improved due to the application of the green walls; for example in both cities of Riyadh and Athens, the thermal comfort improved from “hot”, to “slightly warm” and “comfortable” in most hours of the day and even reached to “slightly cool” and “cool” during late evening and early mornings. Alexandri and Jones (2008) suggest that combination of green roofs and walls would have a much greater cooling effect on mitigation of urban heat island compared to individual application of each strategy.

Cheng, et al. (2010) assessed the potential of vertical greenery on capturing solar heat; their research conducted an experimental study on the application of different clusters of green modules (with various configurations) on the wall of a housing apartment. The results confirmed the significant cooling effect of the vertical greenery with the fact that larger clusters had lower temperatures due to larger thermal mass and ratio of vegetated area. The temperature difference between the substrate and the ambient air temperature was 1^{0}C in average during the day, though this difference could reach to 14^0 C in some afternoons. However, the green substrate was on average 2 ^{0}C warmer than the air temperature during the early hours of evening (17:00 to 20:00) since the moisture and air within the green fabric lowered the process of heat loss. Also Wong, et al. (2010) also studied the thermal performance of 8 different vertical greenery systems on the performance of building and their immediate environment (Figure 2.10).

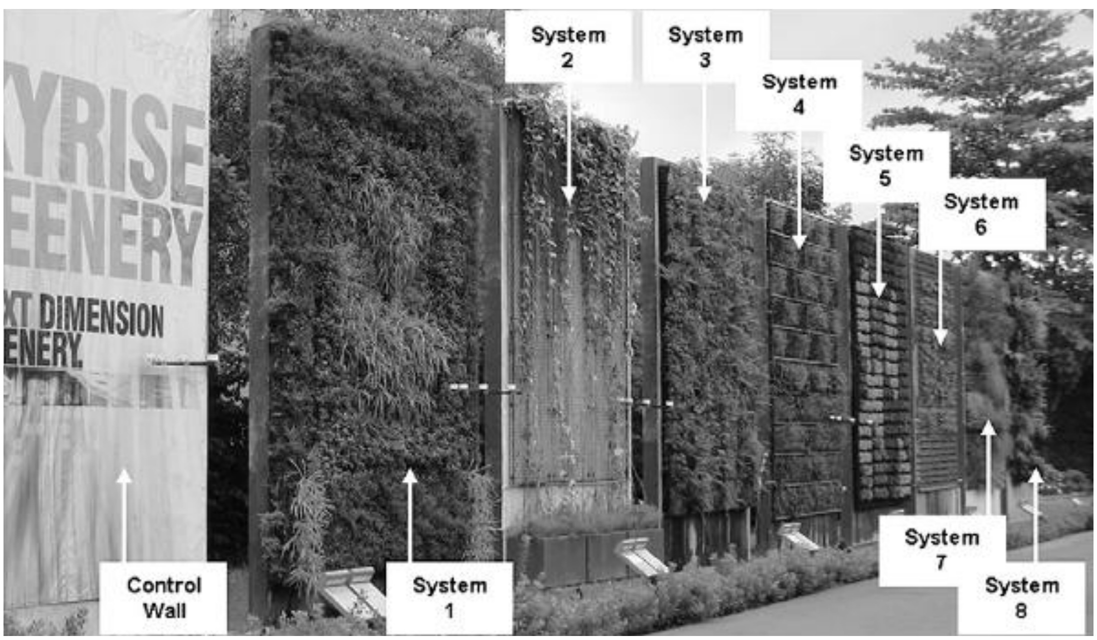


Figure 2.10 Control wall and 8 vertical greenery systems. (Wong, et al., 2010)

The results of this study are in agreement with those of Cheng, et al. (2010) and confirm the effect of greenery in reducing surface temperature of the wall; in this study all the greenery systems had lower temperatures compared to the control wall; however the systems with larger foliage areas and density had larger effects (system 4 & 3, figure 2.10). In terms of the diurnal temperature changes, all the greenery systems showcased the more stable fluctuations of temperature compared to the control wall; this stability could prolong the life span of the wall and reduce costs of maintenance. In order to determine the effect of vertical greenery on immediate environment, Wong, et al. (2010) measured the ambient temperature at different distances from the green walls. The effect of vertical greenery on ambient temperature was found to be highly dependent on the greenery system; for example system 2 (figure 2.10) found to have almost no effect on the ambient temperature while the effect of system 4 on ambient temperature was felt for distances as far as 0.6m.

Table 2.4 shows reductions in ambient temperatures up to 3.3 ^{0}C for wall system 4 at distance of 0.15 m away (Wong, et al., 2010). Based on the large number of vertical surfaces and wall facades in the urban areas, reduction of urban heat island by application of greenery is promising; this is in addition to other direct and indirect benefits of vertical greenery such as reduction of energy use and interior temperatures.

Table 2.4 Summary of ambient temperatures at different distances. (Wong, et al., 2010)

VGS	Temperature (°C)					
	0.15 m away		0.30 m away		0.60 m away	
	Lowest	Highest	Lowest	Highest	Lowest	Highest
Control Wall	26.34	34.85	25.17	33.59	25.17	33.59
1	24.79	31.93	26.34	34.01	25.17	32.34
2	25.56	32.76	25.56	32.76	25.56	32.76
4	25.17	31.52	25.17	31.93	25.95	32.76

2.7 Research Importance

Even though a lot of cities around the world have been tackling the issue of urban heat island for a long time, this phenomenon is considered to be new in some of the fast developing cities around the world. Most of the cities located in the Middle East have been developing at an incredible rate during the last decade; among these cities, Dubai stands out in terms of development in a short period of time. Figure 2.11 shows the tremendous development of Dubai from the year 2000 to 2010; during this 10 year period, larger amount of built up areas has been added to the urban area compared to the added vegetation. One of the most important concerns which were raised by the authorities after the massive developments was Urban Heat Island phenomenon. Dubai municipality conducted an aerial thermal survey of the city in December 2009 (Zacarias,2011); the air born thermal images of Dubai showcased the existence of urban heat island in the city. Dense areas which belong to the older fabric of the city such as Deira and Bur Dubai as well as the industrial areas of Al Qouz were identified to be the hot spots within the city (Zacarias, 2011).

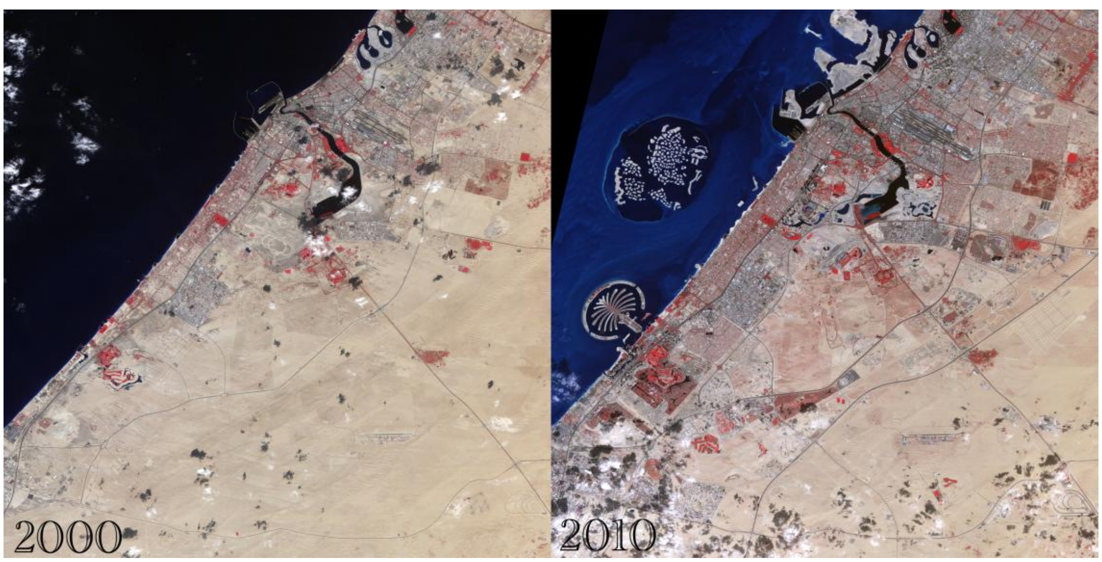


Figure 2.11 Development of Dubai in the 10 years period of 2000-2010; Red color shows vegetation.(Earth observatory, 2009)

Figure 2.12 shows a thermal image snapped from Deira and Bur Dubai area; the grey circles in the figure point out the hot spots in these areas. According to Figure 2.12, building dominated clusters with narrow roads have tremendously higher temperatures than the rest of the areas; these areas are approximately 3-4 ˚ C warmer than the rest of the area. Currently Dubai Municipality is conducting field experiments in these areas, in order to analyze the extent of the UHI more accurately; also the cooling effects of several mitigation strategies such as cool materials and greenery are currently under examination for implementation in the hot spots (Zacarias, 2011).

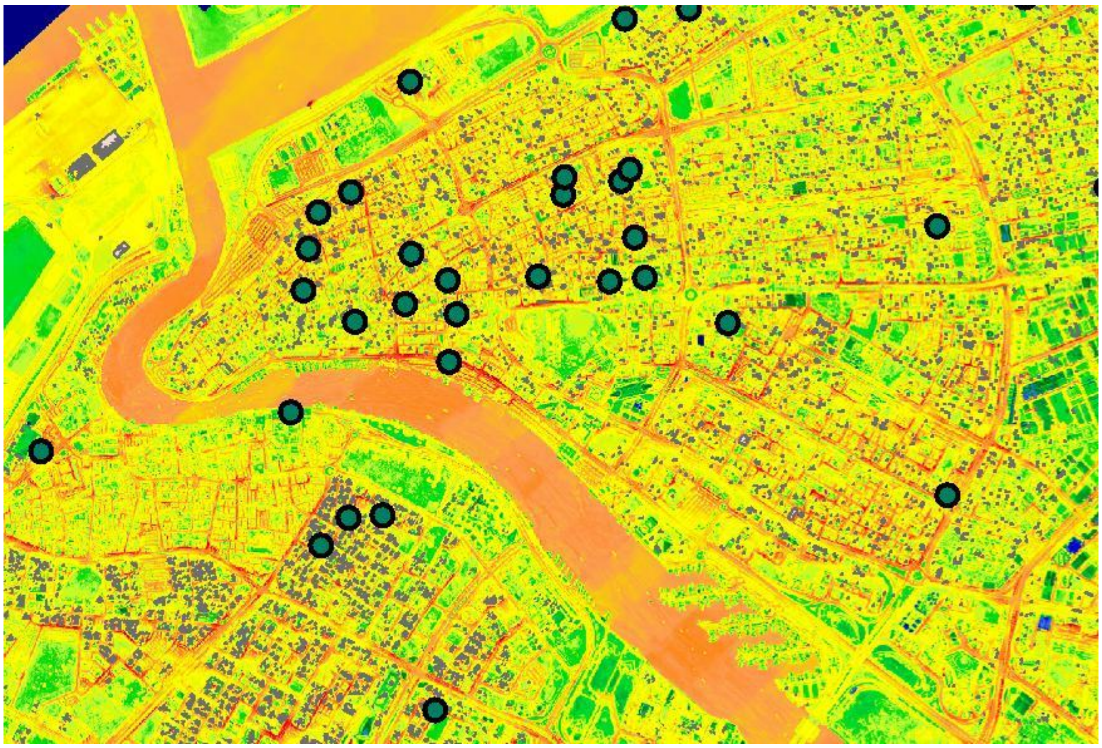


Figure 2.12 Urban heat island in Dubai, snap shot of Deira and Bur Dubai area; the bold circles indicate the urban hotspots. (Zacarias**,** 2011)

2.8 Aims and Objectives

Based on the importance of the effective mitigation strategies (specifically greenery), this research studies the effect of vegetation on mitigation of urban heat island in dense urban areas of Dubai. Even though many studies in the pat have confirmed the positive effects of greenery in reduction of excess heat, there are questions that need clarification before employing any strategy in Dubai. For example, what are the most efficient types of greenery that could be applied? What are the characteristics of urban greenery in terms of density and form? How should urban vegetation be applied in relationship to building structures?

The objective of this research is to test the effects of the vegetation on reduction of excess heat in urban areas; these effects would be tested in terms of type and composition of the greenery as well as density and relationship of the vegetation with buildings. Based on the output of these tests, certain optimal strategies would be selected for application in real conditions; the effects of these strategies would be analyzed through further tests on real urban conditions. Based on the aim and objectives of this research, expected outcomes are as follow:

- Identification of the most effective type and configuration of green fabric which is applicable to dense urban areas of Dubai
- Identification of the optimum density of vegetation which would lead into reduction of excess heat in dense urban areas of Dubai
- Identification of the most efficient way of applying vegetation in relationship to build up structure in urban areas
- Identification of optimal strategies and policies of applying urban vegetation for both newly designed areas and pre-existing areas

CHAPTER 3

Methodology

3.1 Introduction

The body of research in the area of urban heat island has employed several study approaches. In general, the study of urban heat island is considered to be challenging due to the multiple factors contributing to its effect; these factors include small scale processes such as anthropogenic heat, building properties and urban vegetation as well as large scale interactions such as atmospheric and climatic sources. The approaches in studying urban heat island and its mitigation could be classified under two main categories of observational approaches and simulation approaches. Observation approach consists of direct inspection or recording of different interactions that play part in creation and mitigation of urban heat island in the cities. This approach of research could be divided into three different methods including thermal remote sensing, field measurement and small scale modeling. On the other hand, simulation approaches consist of modeling or virtual creation of a real condition in the urban area that contributes to the creation or mitigation of urban heat island .Simulation approach could also be divided into three methods including computer simulation, energy balance model and numerical model.

Each of these approaches has its own abilities and limitations that would be discussed in accordance with examples of studies in this chapter. However, before discussing these methodologies it is important to note that in order to study the urban heat island phenomena, most of the research that has been done in the last decade employed multiple approaches. In contrast, Studies that were done in the past mainly relied on observational approaches and developing numerical models; for example Avissar (1994) developed a large number of numerical simulations in order to study different aspects that contribute to the effect of vegetation in urban environments such as different types of rural and urban areas, different size of urban areas, different percentages of urban vegetation coverage and various atmospheric conditions. Also Wilmers (1988) studied the effect of urban green areas only by measuring the surface temperatures of different urban elements using a handheld thermal scanner; he then compared the collected data from different areas for further analysis and understanding the effect. On the other hand, recent studies take advantage of computational simulation tools beside the conventional approaches. This is due to the fact that, advancements in technology have extended the available tools and equipments that could be used to study the effect of urban heat island and its mitigation; therefore scientists have combined different techniques in order to cover the multiple aspects of the phenomena and gain more accurate results.

3.2 Observation approach

In this section different approaches that are categorized under observation are discussed in more detail through sample papers that employed these approaches as part of their methodology.

3.2.1 Field measurement

In this approach the near surface temperature of different urban areas is measured and compared for further analysis. Field measurement data could be collected in different ways; one is fixed stations in which the data is collected at number of different fixed points within the study area and compared for further analysis. For example Chang, et al. (2007) conducted field measurements at fixed stations in several selected parks in the city of Taipei. The temperature measurements were taken during summer 2003 and winter 2004 using an advanced thermometer called Lutron LM-8000 sensor; this device was installed unto a pole attached to a measuring wheel such that it remained 2m above the surface. For each park 5 measurement points were selected; one inside the park ad four points at the surroundings of the park; the temperature measurements from these points were then used to estimate the cool island intensity of each park as well as a general comparison among all selected parks. On the other hand, Hamada and Ohta (2010) selected 24 fixed stations around a major urban park in order to measure the extent of the effect of this park on microclimate of the surrounding areas. The measurements in this study were also installed on poles 2-3 meters above the ground in surrounding urban areas with different land use such as schools, hospitals, temples etc. Also Giridharan,et al. (2007) and Wong, et al. (2007) used the fixed station field measurement as part of methodology in their study of urban heat island and its mitigation through urban greenery.

Mobile survey is another way of conducting field measurement; in this method data is collected along one or several paths within the urban area. The mean of transportation could be car, public transportation or walk. Won and Yu (2005) employed mobile survey method in their study of green areas in Singapore; in order to better understand the correlation between land use and ambient air temperature mobile surveys were conducted in order to map out the relative humidity and temperature profiles at various regions. The mobile survey was conducted by vehicles that were equipped with observation tubes which consisted of Hobo temperature/RH mini-data logger; the data were collected along several journeys at different times of the day; figure 1.3 shows a graph of collected data in one of the routs. Also Stabler, et al. (2005) selected four transects (routs) based on land use and urban location along four major asphalt roads in order to study the microclimates of Phoenix metropolitan area; in this study near surface temperature and relative humidity were also measured along the routs using a moving vehicle equipped with meteorological sensors. The fixed station and mobile survey are both traditional ways of studying urban heat island effect that were used in some of the earliest studies in this area. These approaches would provide the ability to collect data from real life situations which is normally difficult to model in artificial conditions; therefore in case the data are collected professionally and accurately they could be a good measure for validation of the results from other methodologies. Also with advancements of measurement equipments, it is possible to measure multiple parameters such as air velocity and turbulence fluctuations in order to find correlations between these parameters and the effect of urban heat island.

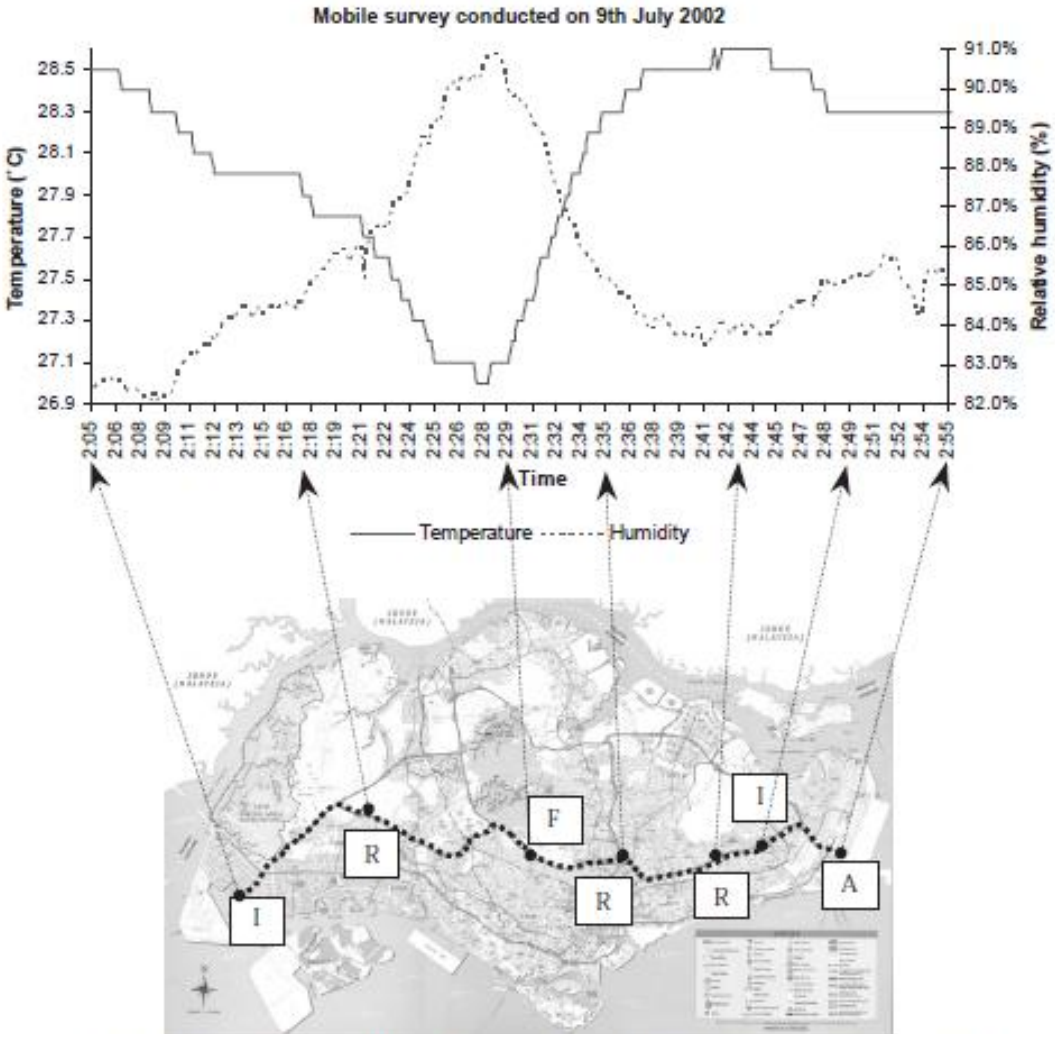


Figure 3.1 Data collected from one of the mobile survey routs (I-industry; R-residential; F-forest; A-airport). (Stabler, et al. 2005)

Despite these benefits, field measurements have several limitations as a single approach of study. The development and installation of measurement equipment is usually time consuming and expensive, therefore limited number of stations or mobile surveys are conducted and only limited numbers of parameters are measured at the same time. As a result field measurement is incapable of providing a three dimensional distribution of all important parameters inside an urban area. Also in terms of data analysis, due to the abundance of parameters that effect UHI and its mitigation it is not possible to draw consistent generalizations based on simple correlations of measured factors and UHI. The other problem with field measurement is that it needs to be carried for a long period of time in order to minimize the effect of unpredictable errors. Regardless of these shortcomings, field measurement has been an important method for studying UHI as a combination with other methods of study which would be explained later.

3.2.2 Thermal remote sensing

Advancements in technology of satellite and airborne/air craft platforms have enabled the researchers to capture thermal remote observations of urban areas. The data collected through these means are the surface temperature of the urban components from top view; this temperature contains the effects of surface moisture, emissivity, albedo and near surface ambient temperature. Different researches have employed thermal remote sensing in different ways, for example Caoa, et al. (2010) used ASTER LST (land surface temperature) satellite image which produces advanced multispectral image. ASTER LST was used to examine the overall pattern of temperature distribution in the city of Nagoya in Japan; however in order to obtain detail information on land use properties and land surface temperatures, Caoa, et al. (2010) used IKONOS image which has 4m spatial resolution. Also Zhanga, et al. (2010) used Landsat 5 TM image of Beijing as a data source to study the relationship between vegetation greenness and UHI. The image includes 7 bands with a 30m spatial resolution; the authors used the third and fourth band in order to extract the NDVI (normalized difference vegetation index) and the sixth band in order to extract the brightness temperature of the study area (Figure 2.3). Also Zhoua, et al. (2011) derived LST (land surface temperature) from the thermal infrared band of a Landsat Thematic image in their study of the effects of land cover pattern on land surface temperature.

On the other hand, Quattrochi (1998) used airborne Thermal Infrared Multispectral Scanner (TIMS) to obtain high spatial (5m) remote sensing data; TIMS data were used to measure thermal energy for 2 general

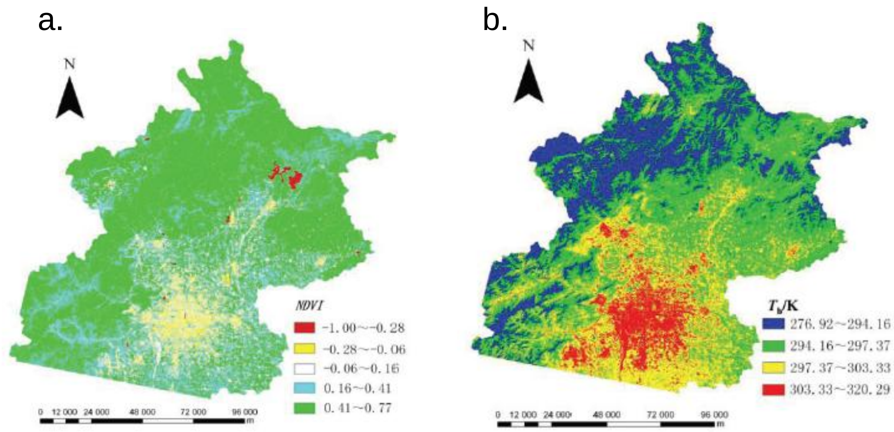


Figure 3.2 Landsat image of Beijing; (a) image band 3 and 4: NDVI; (b) image band 7: brightness temprature. (Zhanga, et al. 2010)

classification and 10 sub classifications of vegetation in Salt lake City, Utah. A flight path which included representative sample of the urban areas in Salt Lake City was selected; then data was collected at approximately 3500m altitude to collect 5m resolution data from the urban surface. Quattrochi (1998) selected six sites along the flight path to assure a full representation of various urban covers including central business district, medium to heavy industrial area, area of native grass with housing, suburban residential area, urban park with extensive tree cover and an urban park with extensive grassy cover.

Thermal remote sensing is a direct observation of the real life condition therefore like field measurement it could be a good measure for validation of the results obtained from simulations. However this technique is extremely expensive and it is very difficult to capture steady images of the urban areas. This limitation could be related to the ability of the equipment itself or the weather conditions such as possibility of clouds, dust or high humidity over the urban areas. However the main concern with this technique is that the collected data relates to the upward spatial patterns of thermal radiance from the surfaces only and the atmospheric interactions and ambient air temperatures are disregarded. The other problem is that remote sensing only collects data from the surfaces that are visible from the top view while most of the urban surfaces are three dimensional and they all play a role in microclimates of urban environments.

3.2.3 Small scale modeling

The other approach which has been used in studying the effect of greenery on urban heat island is small scale modeling. This approach consists of building a prototype of a real condition and examining the prototype under either outdoor conditions or wind tunnels. Small scale modeling has been mainly used for studying the effects of roof garden and vertical greenery on UHI; for example Wong, et al. (2010) installed 8 different vertical greenery systems on the wall of an urban park in order to test their effects of different types of green walls on microclimates. These 8 types cover a wide range of green walls from simple green façade to complex living wall system; dimensions of all 8 types are similar and they are all measured against a bare concrete control wall which is 4m wide and 8m high. Measurements of the temperatures are done at 2 layers; one is the surface of the wall and the other is the temperature of the substrate surface. In order to measure the ambient air temperatures, data loggers are placed at intervals of 0.15m, 0.3m, 0.6m and 1m away from the wall surface and temperatures are measured at each of these distances. One of the main concerns in this approach is that it is difficult and sometimes impossible to establish similarity between the real condition and the prototyped condition. In fact it is not possible to implement all the playing factors in the artificial condition and therefore small scale modeling is suitable for analyzing the effects of limited number of parameters. The other problem with this approach is that it is very time consuming and costly to create small scale models and accurately imitate the real conditions. For example Wong, et al. (2010) had to spend a long time on design, installation and growing of the green walls in their study which all cost considerable money.

3.3 Simulation approaches

Various simulation approaches have been developed to study the effect of greenery on urban heat island. In these approaches the effect of greenery is analyzed under a virtual condition i.e. a numerical model or a computational simulation. However due to the complexity of the playing factors, major simplifications are usually required in these approaches. Regardless of these simplifications the advancements in technology and computational softwares have enabled researchers to study large scale problems. In this section different approaches that are categorized under simulation are discussed in more detail through sample papers that employed these approaches as part of their methodology.

3.3.1 Energy balance

Energy balance method uses the law of conservation of energy for a given situation in an urban area. This method considers the atmospheric interactions, turbulence fluctuations and heat fluxes through different analytical or empirical equations. One of the models that is created in this method is the Urban Canopy Model (UCM) which uses energy balance equation to determine the energy exchange between urban surfaces and ambient air for a given volume in an urban canopy. This model predicts values of ambient and surface temperatures of streets, buildings and pavements with the given volume. In this model all surfaces within the control volume are treated like connected electrical nodes; then energy balance equation which is derived from conservation of energy law is applied to each node to create a matrix of surface temperatures; by solving these matrices a general domain of surface temperature are attained. Ayata, T. et al. (2011) used energy balance approach in their investigation of heat fluxes at a green roof. They used the equation (3.1) in determining the heat fluxes from a green roof.

$$Rn - G - L - H = 0 \quad (3.1)$$

Rn is the net radiation from the sun, G is the soil heat flux on the roof, L is the latent heat flux and H is sensible heat flux from the green roof. In this equation latent heat flux is directly derived from the evapotranspiration rate of the vegetation on the roof. In this study, each parameter in the equation was calculated through other equations independently and used to determine the heat fluxes at a green roof. One of the biggest limitations of this approach is the absence of air velocity in the energy balance equation as this parameter is important to determine the sensible and latent heat flux and formation of atmospheric interactions. Another problem is existence of variables that are inconsistence to one another in terms of time steps; for example thermal storage of the urban canopy materials has different time steps compared to heat fluxes. The other limitation is providing three dimensional databases for geometry of urban structures, which is a very expensive and time consuming process therefore in most of the models the city is replaced with homogenous columns of buildings. Also the complexity of urban structures is replaced with limited simple grids on ground, roofs and walls. All these limitations result in a weak spatial resolution for the energy balance models.

3.3.2 Numerical model

Numerical model is a simulation approach which has been used for a long time in the study of urban heat island. In this approach, depending on the focus and the parameters of the study, a model is developed using series of mathematical equations. Some of the studies in this area have solely employed the numerical method; for example Alexandri and Jones (2008) developed a two dimensional dynamic micro-scale model which described heat and mass transfer in a typical urban canyon (Figure 3.3). In this model the effects of heat and mass transfer, building materials, soil and vegetation have been studies by solving differential equations with finite differences approximations. In this study plants have been treated as a layer with canopy leaves and the air among them; then parameters such as density of leaf tissue, specific heat capacity of leaf tissue, leaf surface temperature, net heat gain from radiation and net latent heat loss have been used in an equation to study the effects of the plants in decreasing the temperature within the urban canopy. Also (Avissar, 1994) used a two dimensional numerical model in order to study the potential effect of vegetation on urban environments. In this study, the authors developed a land surface parameterization method called patchy land-atmosphere interactive dynamics (PLAID) where the land surface is assumed to consist of mosaic patches. The patch classes that are mostly associated with urban areas are industrial, residential, commercial and undeveloped; each of these classes consist of certain percentage of greenery and detailed environmental conditions such as temperature and humidity. Then series of numerical simulations were developed for different patches and their results were compared to draw further conclusions regarding the effect of greenery on thermal environment of the urban areas.

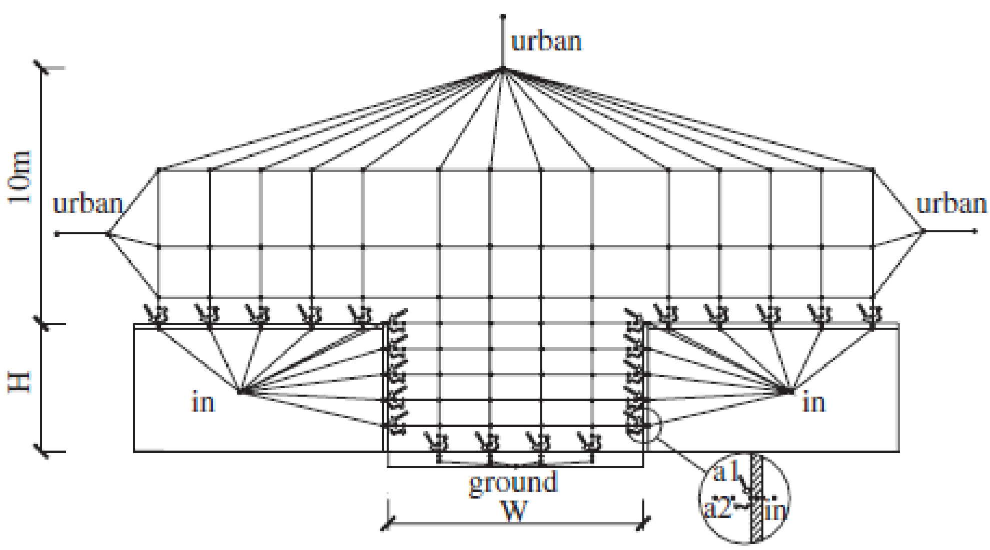


Fig. 1. Two-dimensional canyon model.

Figure 3.3 Two-dimentional canyon model. (Alexandri and Jones , 2008)

On the other hand, some of the studies use numerical simulation in combination with other studies. For example Takebayashi and Moriyama (2009) in their study on the effect of green parking lots on mitigation of urban heat island, used numerical method in order to estimate the heat flux from each parking space. The expression used in this calculation used convection heat transfer, surface temperature and air temperature in order to estimate the amount of sensible heat flux. The authors used the mean surface and air temperatures from their earlier observational studies; also they used the collected wind velocity data in order to calculate convection heat transfer in order to calculate sensible heat flux.

Some of the limitations associated with this method is that due to the complexity of the urban heat island, usually major simplifications are required. These simplifications are required in case of atmospheric interactions, turbulence, providing boundary conditions and land use, land cover data base.

3.3.3 Computer simulation

One of the newest and most important approaches in the study of urban heat island is computer simulation which is evolving every day. Computational Fluid Dynamics (CFD) softwares are the most important category of softwares used in the studies of urban heat island. These softwares solve all the equations related to the fluid inside the urban areas and therefore they are capable of estimating the distribution of urban heat island and its relationship to the geometry and configuration of urban environments. However, CFD simulation is not very useful in studying the microclimatic effects of vegetation in the urban areas. This type of study requires softwares that focus on surface-plant-air interactions within the urban areas. Due to the complexity of these interactions, there are few types of software that are capable of analyzing microclimatic effects of vegetation in the urban environments. Envi-met is one these softwares which is a three dimensional microclimatic model designed to analyze the interactions among surfaces, plants and air in the urban environments. This software is developed based on the fundamental laws of fluid dynamics and thermodynamics; it is capable of simulating the flow around and between buildings, exchange processes of heat and vapor at the ground surface and at walls, turbulence, exchange at vegetation and vegetation parameters, bioclimatology and particle dispersion (Envi-met,2004) . In their evaluation of the effect of greenery on the microclimate of a campus, Wong and Jusuf (2008) used computer simulation with Envi-met software. The authors first conducted GIS based surveys in order to quantify the existing greenery as well as potential rooftop greenery on the campus. Then they used Envi-met software in order to predict the temperatures on the campus; the simulation was conducted in two stages. In stage one, two scenarios of the existing master plan of the campus and existing master plan with additional trees were simulated in Envi-met and the results of the two scenarios were compared. The second stage, involved modeling a part of the campus with four different scenarios of as designed, application of grass on the rooftop, application of trees on the rooftop and application of trees on the rooftop and site (Wong and Jusuf, 2008); each of these scenarios were simulated in Envi-met and their results were compared.

Also Fahmy and Sharples (2009) as well as Yu and Wong (2006) used Envi-met simulations in order to study the cooling effects of urban greenery on reduction of UHI. Fahmy and Sharples (2009) used Envi-met software in their investigations of urban form as a passive thermal comfort system in the urban areas of Cairo. In this study two scenarios of different density and population in the urban areas of Cairo were developed; Envi-met simulations were then used to predict the level of thermal comfort in these urban areas. On the other hand, Edward, et al. (2011) used Envi-met in their study of cooling effects of greenery in the high density city of Hong kong. They created 33 different simulations each employing different sets of parameters including, building height, percentage of greenery cover and type of green cover. These scenarios were designed to determine the location, type and amount of greenery necessary in the urban environments of Hong Kong.

The major limitation with computer simulations is their verification of accuracy; this verification process varies based on the focus of the study as well as variable of interest. Beside, simulation models require certain level of simplifications compared to their real condition in an urban area. For example, in case of Envi-met the model is created on a strict rectangular grid; while in reality the city grids are not based on any strict grids. The other limitation is that it is not possible to include all the variables in one model; again in case of Envi-met it is not possible to apply materials to the buildings or consider sources of anthropogenic heat in the urban areas.

3.4 Research methodology

As mentioned in the previous chapter, the main aim of this research is to investigate the effect of green fabric application on mitigation of urban heat island in dense urban areas of Dubai. Based on the description of various methodologies explained in previous chapters, computer simulation is selected as the main study approach in this research. The methodology of this research consists of three stages of software validation, modeling and simulation as well as data analysis and conclusion. In this section, the choice of methodology is justified first, and the selected software is validated as the main simulation tool.

3.4.1 Justification

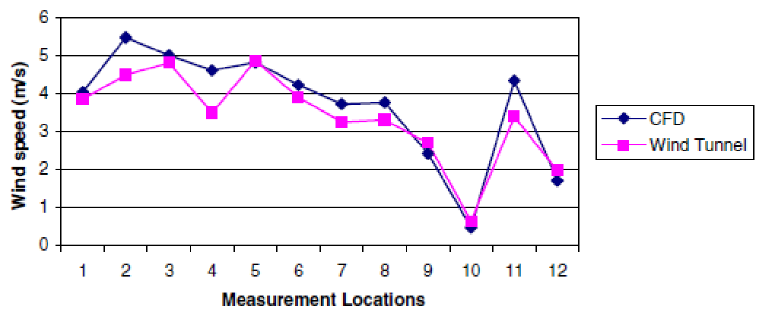
The first reason behind selecting computer simulation is time; compared to other study approaches computer simulation is a faster and more efficient approach. Urban greenery as the main focus of this research is a natural element and a study approach such as field measurement needs to be carried over long periods of time in different conditions in order to reach valuable results. Also in some cases such as remote sensing, advanced equipment is needed in order to carry a study on the urban greenery; both preparation of equipment and data collection are expensive processes which are out of the scope of available resources for this research. Furthermore, approaches such as numerical and energy balance require over simplified models of the real conditions which are again in contrast with wide range of aspects that effect urban greenery and reduction of urban heat island. On the other hand, computer simulation enables the research to develop a more realistic model of the real conditions and focus on the effect of multiple variables simultaneously. Plus computer simulation provides a faster and cheaper mean to study the effect of urban greenery and is a suitable solution of methodology with respect to resources available for this research.

The main computer simulation tool which was selected in this research is ENVI-met V3.1. This software consists of three components; the first is ENVI-met Eddi which is the main tool for modeling the area. Envi-met Eddi consists of a grid on which the model is constructed; this software enables the input of buildings with different heights and forms, different types of vegetation such as trees, grass or hedge as well as different types of ground cover such as asphalt or different kinds of soils. The second component is Envi-met Configuration Editor which is used to input the initial data such as climatic data simulation time and duration, building data, etc. The third component is the actual simulation engine which uses the input files provided by Envi-met Eddi and Envi-met Configuration in order to run the simulation. Therefore Envi-met provides sufficient means to input most of the necessary data that are related to the objectives of this research. Based on research objectives and software application and abilities that were explained above, Envi-met is selected as the main simulation tool in this study.

3.4.2 Software Validation

Some of the previous studies have verified the validity of ENVI-met software. Wong, et al. (2007) in their study of the impact of vegetation on the microclimate of a university campus in Singapore, compared the thermal data that were acquired through three different methods; satellite image, field measurement and Envi-met simulation. The satellite image was super imposed on the campus image in order to identify the hot and cool spots; then these images were compared with the results of the field measurement in order to verify the distribution of hot and cool spots. The simulated image was then used in parallel with these two sets of data in order to validate the correct distribution of temperatures in the simulated data; in all three methods, clusters of greenery showed lower temperatures compared to clusters of buildings. In this study there was no attempt of comparing the exact temperatures of all three methods in order to match the simulated data with the actual data and the researchers only relied on matching distribution of temperatures for all three methods. On the other hand, Priyadarsini, et al. (2008) in their study of the key factors contributing to the urban heat island in Singapore, attempted to validate the results of CFD simulation and real condition data from a wind tunnel experiment and field measurements. Figure 3.4 shows the results of the comparisons of wind tunnel experiment and field measurements with CFD simulations; as shown in the figure, the CFD simulation has the same profile as the real condition data.

a.



b.

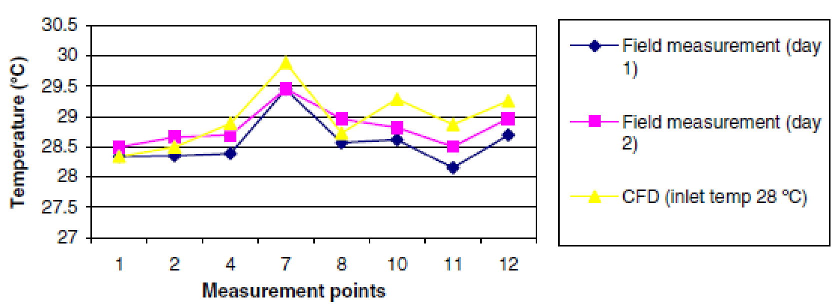


Figure 3.4 Software validation. (a) comparison of CFD and wind tunnel results. (b) Comparison of simulated temperatures with measured temperatures. (Priyadarsini, et al, 2008)

Despite the fact that the data do not match completely and there is a level of discrepancy, the authors have relied on the overall distribution and profile of the data. Since some factors in the real conditions that contribute to thermal data are absent in simulation condition (in case of this research, anthropogenic heat is one these factors), it is not possible to gain results that are completely consistent with the real condition.

Even though Envi-met has been verified in some of the previous studies, the accuracy of the software is required to be reconfirmed for the purpose of this study. In order to validate the Envi-met software, thermal images of Dubai were acquired from the Dubai municipality environmental studies section. Figure 3.5 (a) shows an urban block located in Deira area which is considered as a part of old and dense urban areas in Dubai; Figure 3.5 (b) shows the infrared image of the same urban block which was taken few hours after the sunset during early December 2009 (Zacarias, 2011).

Figure 3.5 Images of an urban block in Deira, an old dense urban area in Dubai. (a) Google earth image. (b) infrared image taken few hours after sunset during early December 2009.(Zacarias**,** 2011)

It is important to note that the aerial thermal surveying of Dubai was done during winter due to the existence of excessive humidity and dust in the ambient air during the summer times. Therefore for the purpose of accuracy and clarity the thermal survey was performed during a calm winter day (Zacarias, 2011). On the other hand, since the software is incapable of simulating very large areas at proper resolution, only a portion of the selected urban block (shown in Figure 3.5) was modeled in Envi-met; Figure 3.6

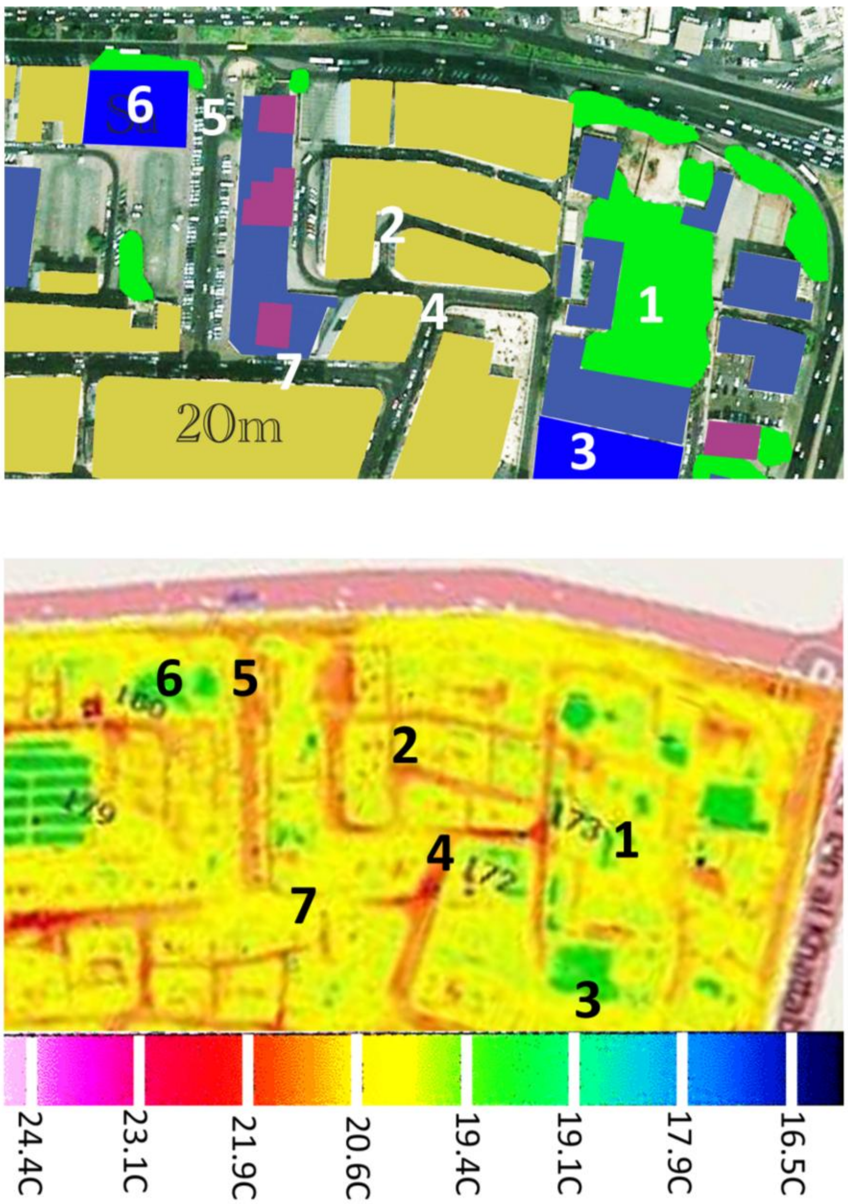


Figure 3.6 selected urban block with actual thermal image .

shows the modeled area and its actual thermal image. This simulation was run during 3rd and 4th of December 2009 (48 hours); the initial inputs of climatic information used for this simulation are as follow:

1. Initial Temperature Atmosphere : 24^{0}C (average daily temperature during early December in Dubai)

2. Wind Speed in 10 m ab. Ground [m/s] : 5.5 m/s (most frequent wind speed during December in Dubai)

3. Wind Direction (0:N..90:E..180:S..270:W..) : 290 or North West (most frequent wind direction during December in Dubai)

4. Relative Humidity in 2m [%] : 60 % (average daily humidity during December in Dubai)

Figure 3.7 shows the simulated thermal maps of surface temperatures for the selected urban area from 5pm to 20pm; a quick comparison of these images with the actual thermal image in Figure 3.6 indicates that the pattern of temperature distribution of simulated images matches the actual image. For example the central narrow streets show high temperatures while planted areas show cooler temperatures.

Since the exact time of the actual thermal image is unknown (it is only known that the image was taken few hours after the sunset) 7 spots have been selected and the exact temperatures of these spots have been compared against the temperatures of the actual image for each hour in Table 3.1. In order to measure the closeness of the simulated data to the actual data, the “difference in value” which is the difference between the real and simulated data has been calculated for each spot; a comparison of the difference in value for all hours indicates that during the hour 19:00, the difference is the lowest which means that this hour has the closest results to the real image.

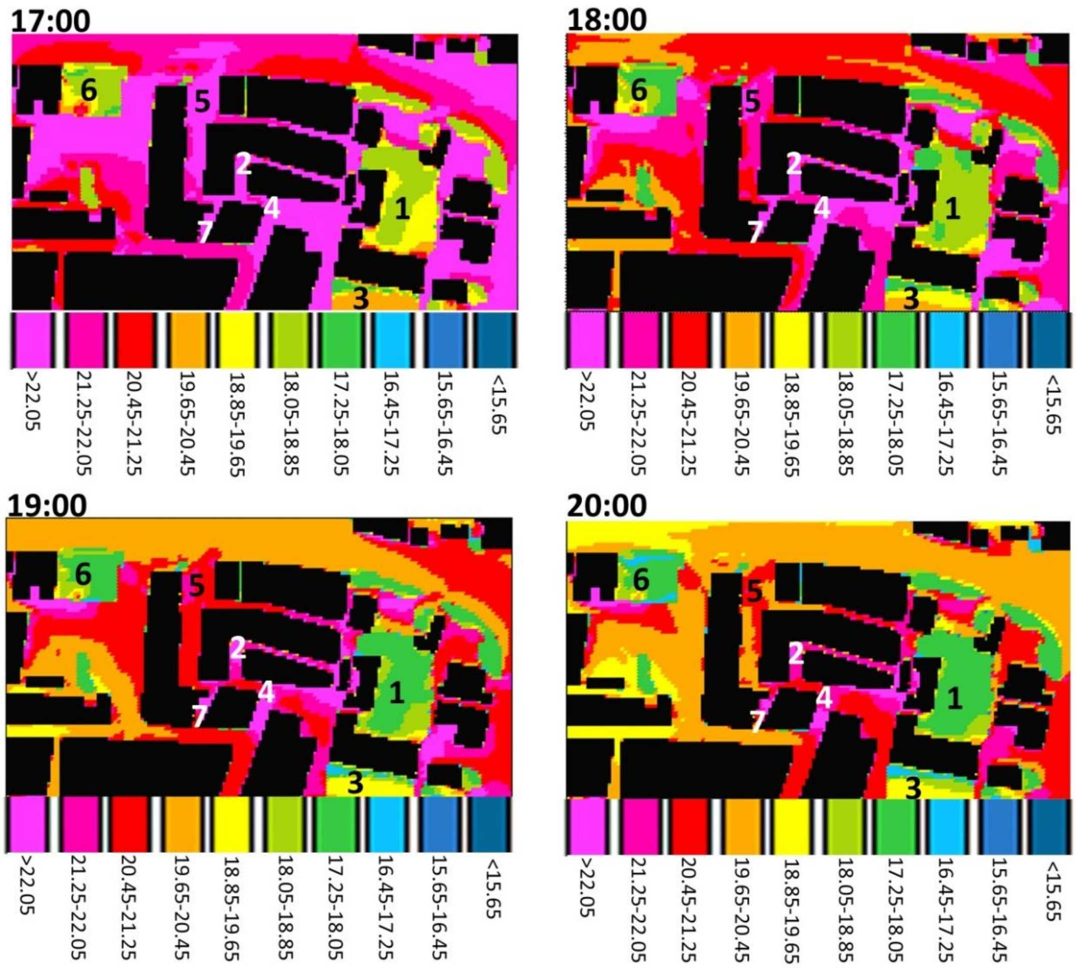


Figure 3.7 Simulated maps of surface temperature for the selected urban block from 17:00 to 20:00.

Also during hours 18:00 and 20:00 the results tend to be very close to the actual image and as the temperatures move away from these 3 hours the difference in value increases. Therefore it is very likely that the real image was taken around these three hours.

Table 3.1 Comparison of the simulated temperatures of 7 selected spots against the actual image temperatures from 17:00 to 20:00. (Continue to next page)

time	Spot number	Actual image temperature (^{0}C)	Simulated image temperature(^{0}C)	Difference in value
17:00	1	19.1	18.45	0.65
	2	21.9	22.05	0.15

Table 3.2 Comparison of the simulated temperatures of 7 selected spots against the actual image temperatures from 17:00 to 20:00. (Continue to next page)

	3	19.25	20.05	0.8
	4	21.9	20.05	1.85
	5	21.9	20.05	1.85
	6	19.1	18.45	0.65
	7	20.6	20.05	0.55
18:00	1	19.1	18.45	0.65
	2	21.9	22.05	0.15
	3	19.25	19.65	0.4
	4	21.9	21.65	0.25
	5	21.9	21.65	0.25
	6	19.1	18.45	0.65
	7	20.6	21.25	0.65
19:00	1	19.1	18.65	0.45
	2	21.9	22.05	0.15
	3	19.25	19.25	0
	4	21.9	21.65	0.25
	5	21.9	21.65	0.25
	6	19.1	18.65	0.45
	7	20.6	20.45	0.15
20:00	1	19.1	18.45	0.65
	2	21.9	21.25	0.65
	3	19.25	19.25	0
	4	21.9	21.65	0.25
	5	21.9	21.25	0.65
	6	19.1	18.05	1.05
	7	20.6	20.85	0.25

Based on the verifications of previous studies and validation process that was done in this research, it could be concluded that the simulation of microclimates of urban areas in Dubai by using the ENVI-met software could be promising and would yield into results close to the real conditions. In the next chapter, selection of parameters, configuration of different tests and model set up would be explained in detail.

CHAPTER 4

Model Setup

4.1 Introduction

The investigations of the effect of greenery in this research are done in two parts. Part one of the research aims to identify the most effective strategies in general; therefore the tests in this part of the research are performed on simplified conditions. Part Two of the research utilizes the results of Part One in order to investigate the effects of greenery in reduction of urban heat island in real urban areas of Dubai. This chapter discusses the selection of parameters and variables as well as detail explanation of the process of modeling setup in ENVI-met.

4.2 Parameters

Part One of the research mainly focuses on the effects of 3 parameters of urban vegetation on reduction of heat in a simplified urban condition. These parameters include formal composition of green urban fabric (focuses on the type of greenery including grass, trees, green roof), density of green fabric (which focuses on Leaf Area Density (LAD) of trees) and location of green fabric vs. grey fabric. For each parameter, a range was defined based on the available variables in ENVI-met; Table 4.1 showcases each parameter and its defined range.

Table 4.1 Selected parameters and their range (Continue next page)

Parameter	Range
Formal composition of Green Fabric (p1)	1.Trees and green roof 2.Grass and green roof **3.Grass and trees** 4. Trees without grass 5. Grass only Note: “Green Roof” implies roof covered half in grass and half in hedges
Density of Green Fabric(p2)	1. Trees with low LAD value 2. Trees with medium LAD value 3. Trees with high LAD value

Table 4.1 Selected parameters and their range (Continued)

Green fabric Vs. Gray fabric relationship(p3)	1. Centralized green fabric with surrounding gray fabric 2. Centralized gray fabric with surrounding green fabric 3. **Layering of grey and green fabric**

In Table 4.1, the bold values in the range of each parameter are default values which are constant values when testing other parameters. Based on Table 4.1, a test matrix is developed for each parameter; table 4.2 to 4.4 display different tests investigating the effects of individual parameters.

Table 4. 2 Tests investigating P1: Formal Composition of Greenery (Grass, Green Roof, Trees)

Test	P1	Fixed parameter p2	Fixed parameter p3
P1-1	Trees and green roof	Medium Density	Layering of grey and green fabric
P1-2	Grass and green roof	Medium Density	Layering of grey and green fabric
P1-3	Trees and grass	Medium Density	Layering of grey and green fabric
P1-4	Grass Only	Medium Density	Layering of grey and green fabric
P1-5	Trees without Grass	Medium Density	Layering of grey and green fabric

Table 4.3 Tests investigating P2: Density of Green Fabric (LAD values of trees)

Test	P2	Fixed parameter p1	Fixed parameter p3
P2-1	Low density	Grass and trees	Layering of grey and green fabric
P2-2 (3)	Medium Density	Grass and trees	Layering of grey and green fabric
P2-3	High density	Grass and trees	Layering of grey and green fabric

Table 4.4 Tests investigating P3: location of green fabric vs. grey fabric

Test	P3	Fixed parameter p2	Fixed parameter p1
P3-1	Centralized green fabric with surrounding gray fabric	Medium Density	Grass and trees
P3-2	Centralize gray fabric with surrounding green fabric	Medium Density	Grass and trees
P3-3	Layering of grey and green fabric	Medium Density	Grass and trees

These tests are going to be applied on a simplified urban block which was designed to determine the effect of individual parameters. In the next sections, different variables and the simplified model are explained in more detail.

4.3 Variables

Different variables play part in interactions of greenery and built structures in the urban areas. In fact, there are number of interconnected variables contributing to these interactions. ENVI-met enables the consideration of number of these variables in simulations. In this research some of these variables are fixed variables while some are independent and dependent variables. Fixed variables are those that remain constant through all the simulations. These variables are fixed according to the focus of the study which is “the urban greenery”. Wind speed, wind direction, average temperature and relative humidity are fixed variables that depend on simulation day and time setup. In addition, variables such as building density, albedo value of walls and roofs, heat transmission values of walls and roofs and the inside temperature of the buildings are also kept fixed in all simulations. Keeping these variables constant through all the simulations ensures that results of the simulations are purely affected by the independent variables. Beside considering the fixed variables, it is important to note that all the simulations in this research are run in both cold and hot seasons in

Dubai; therefore 21st of July has been selected to represent summer and 21st of January has been selected to represent winter conditions. Tables 4.5 and 4.6 show the values that were given to all fixed variables for two seasons of summer and winter. As mentioned in the previous section, 3 parameters of formal composition of green urban fabric (p1), density of green fabric (p2) and green fabric vs. grey fabric relationship (p3) are selected for study in this research. The hourly average surface temperature is the output value that's is going to be measured after the input of all the variables in tests that were defined in Table 4.2 to 4.4.

Table 4.5 Fixed Variables for two seasons of summer and winter

Season	Wind speed (m/s)	Wind direction (degrees)	Initial temperature (K)	Specific humidity in 2500m (g Water/kg air)	Relative humidity in 2m (%)
21st of July (summer)	7	293	308.15	7	53
21st of January (winter)	4	315	289.15	7	66

Table 4.6 Fixed variables for both seasons of summer and winter

Fixed variable	Value
Inside temperature of buildings (K)	300
Heat Transmission Walls [W/m²K]	2
Heat Transmission Roofs [W/m²K]	1
Albedo Walls	0.1
Albedo Roofs	0.1

4.4 Base Test

In Part One of the research, the selected parameters are tested based on the test matrix that was developed in Tables 4.2 to 4.4. It is essential to note that this part of the research purely aims to identify the most effective configurations of urban vegetation that leads to considerable reduction of heat in the urban areas. In order to standardize the condition of the built up area and direct all the focus on the vegetation, a simplified urban block was designed for this part. This simplified urban block which measures 192m x

120m is referred as “base-test”. Figure 4.1 shows the ENVI-met model of the simplified urban block; the model area is developed on a 64 x 40 grid of points each measuring 3m x 3m.

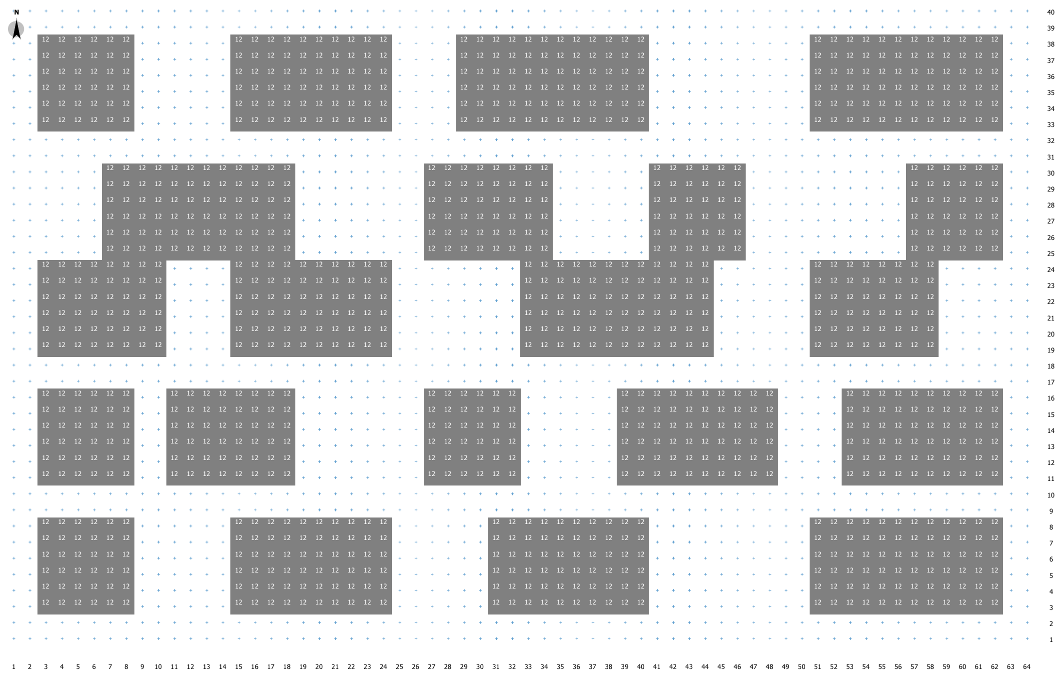


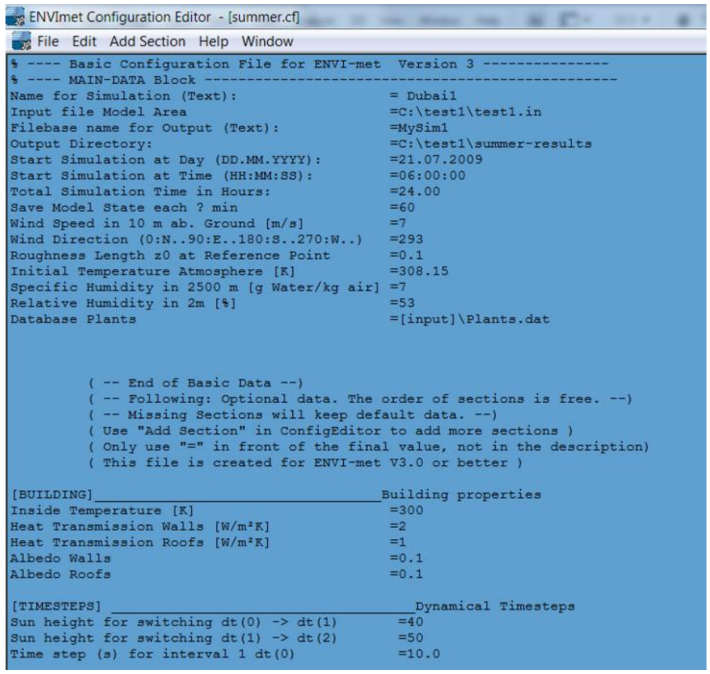
Figure 4.1 ENVI-met model of developed simplified urban block referred as ”base-test”.

The area of the buildings covers 1128 (45%) points out of 2560 total number of points and leaves 1432 points as extra space to be used for inserting roads and greenery. The ratio of building and empty space percentages, enable the possibility of inserting enough greenery in the model. In the base test all these extra spaces are simply covered by sand and asphalt, mimicking a typical situation in Dubai. It should be noted that the number of building points refer to the fixed variable of building density which is constant in all tests. The base-test is manipulated according to the values of three parameters for each individual test in Tables 4.2 to 4.4. These models would be explained independently later in this chapter.

Beside the input model for running a simulation, ENVI-met requires a “Configuration” file as well. Values of fixed variables, timing details, input and output information are set in this file. Figure 4.2 shows snapshots of the

ENVI-met configuration files for both summer and winter cases. The values of different variables are based on values in table 4.5 and 4.6 and the simulation runs to calculate conditions of a full day (24 hours).

Summer



Winter

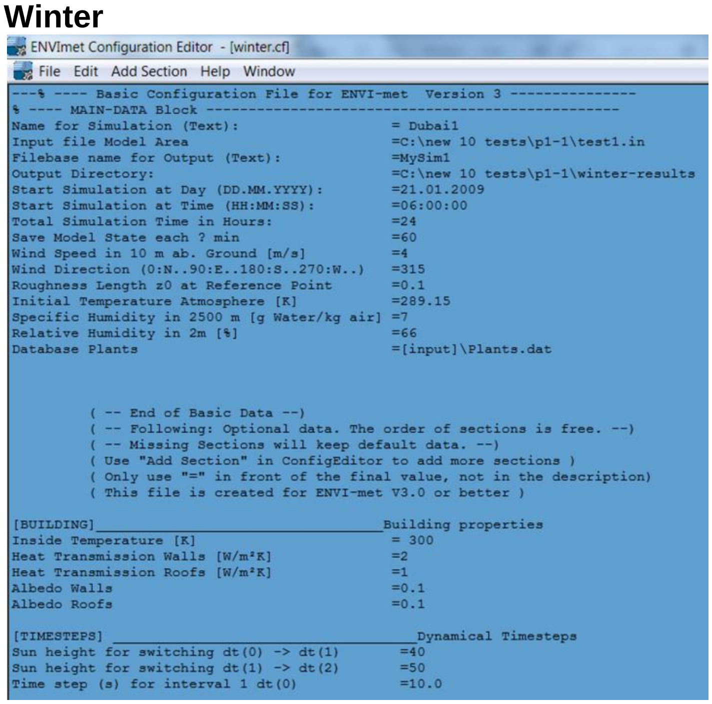
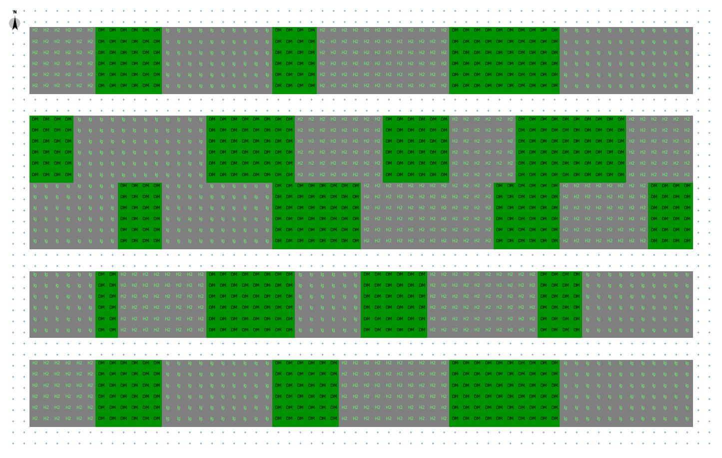


Figure 4.2 ENVI-met Configuration files for summer and winter.

4.5 Model set up for tests investigating Formal composition of Green Fabric (p1)

This parameter “the formal composition of the urban fabric” investigates the effect of the different types of vegetation. Greenery in the urban areas, could either be applied on empty spaces (any place without buildings) or on the roof of buildings (green roof). Each test under this parameter aims to measure one possible condition of applying grass, trees or green roof in the urban areas. Figure 4.7 shows two samples from the ENVI-met models that investigate the effects of Parameter 1.

P1-1



P1-2

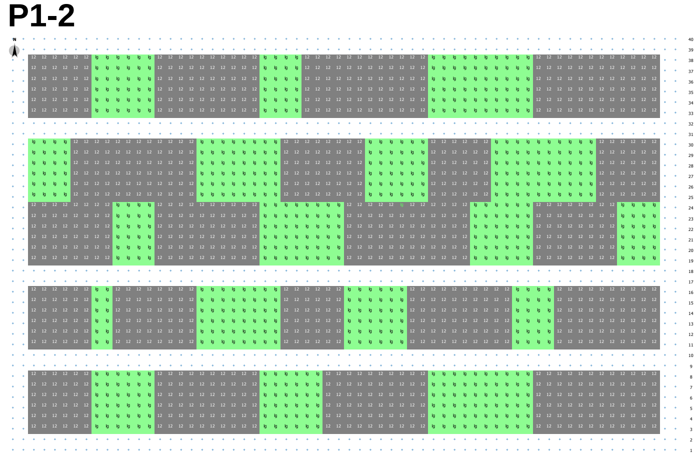


Figure 4.3 Sample of ENVI-met models of tests investigating Parameter 1 (formal composition of green fabric)

For example, in model P1-1 trees and green roofs are inserted in the available empty spaces of the base test while in model P1-4 only grass is inserted in the empty spaces. In all the models investigating Parameter 1, values of the other two parameters are fixed; meaning the density of greenery is kept as medium (p2) and the form of greenery is layering of green and grey fabric (p3).

4.6 Model set up for tests investigating Density of Green Fabric (p2)

Three tests were performed under parameter 2 aiming to investigate the effect of the density of urban greenery. In this research, density of greenery refers to the density of tree canopy which is measured through “Leaf Area Density” or LAD value; LAD is a measure of the density of tree canopy in terms of area of layers cut through the canopy and the overall canopy volume. ENVI-met enables definition of different LAD values for different types of plants used in the model. In this part, 3 types of trees are used in each model, the LAD values of these trees range from low, medium and high values. ENVI-met defines 10 LAD values for each tree; for example, values of the medium LAD tree are 0.075, 0.075, 0.075, 0.075 ,0.250, 1.150, 1.060, 1.050, 0.920 (these values are built-in) . It is important to note that in this test the values of the other two parameters are fixed as well; meaning trees and grass are used as formal composition of the greenery (p1) and relationship of green vs. grey fabric is layering (p3). Figure 4.4 shows a sample model from all the tests investigating parameter 2.

4.7 Model set up for tests investigating Location of Green Fabric vs. Grey Fabric (P3)

This parameter aims to measure the effect of the relationship between the location of green fabric and grey fabric, through three different configurations. Figure 4.5 shows the models developed with different configurations of grey fabric and green fabric. All three models share the same amount of grass and trees despite of their difference in the form of buildings and greenery. Also, in these tests the values of two other parameters are constant,

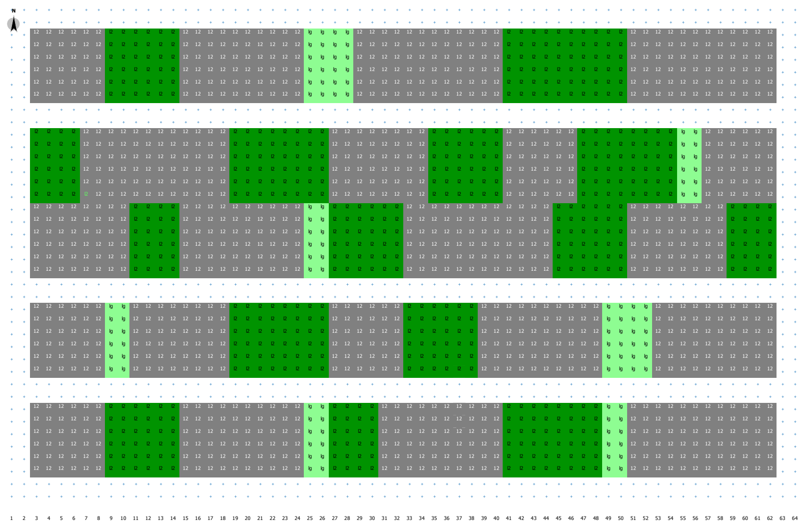
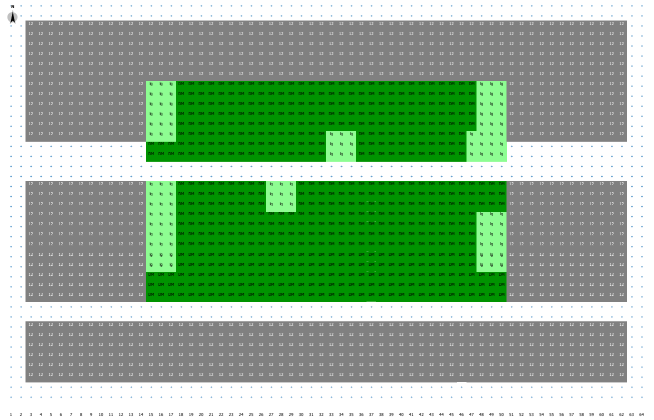


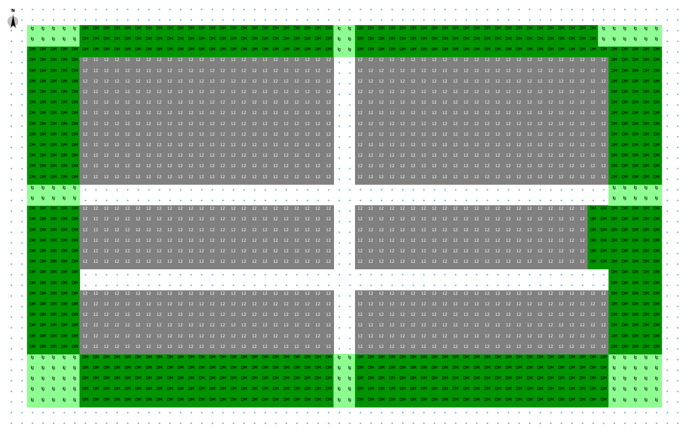
Figure 4.4 Sample model from the tests investigating Parameter 2 (Density of Greenery)

meaning, the composition of the green fabric is combination of grass and trees (p1) and the density of the greenery is medium (p2). The results obtained from all the tests investigating the three parameters would be evaluated based average hourly surface temperatures. For each parameter, surface temperatures obtained from different tests would be displayed in the same graph for further comparison and analysis. Next chapter would focus on the analysis of data and discussion of the results.

P3-1



P3-2



P3-3

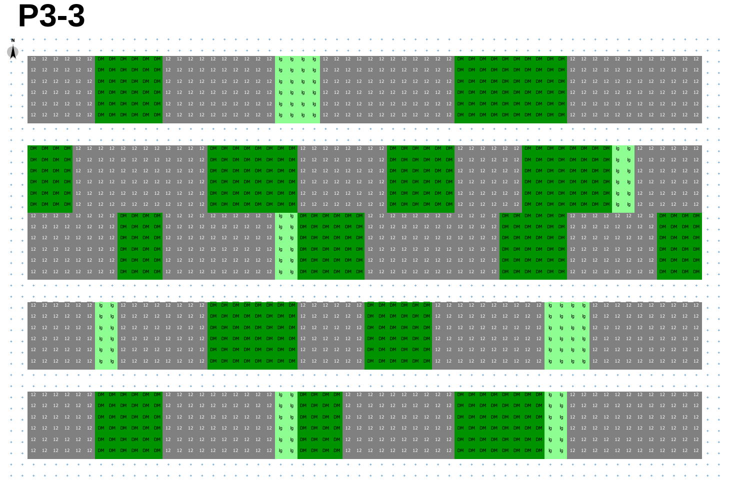


Figure 4.5 Sample model from the tests investigating Parameter 3 (Location of Green Fabric vs. Grey Fabric)

CHAPTER 5

Model Setup

5.1 Introduction

After the completion of all simulation models, the data were extracted and processed to analyze the results. In this chapter the results from Part One of the research are analyzed and discussed in detail. Based on the results of this part, certain “Optimal Strategies” are selected for implementation in real urban conditions. The optimal strategies are selected based on specific criteria which would be discussed later in this chapter. Final sections include Part Two of the research which focuses on the application of Optimal Strategies in real conditions and discussion of the results from this part of the research.

Before going into more details, it should be noted that all the tests are compared based on the average hourly surface temperatures. As discussed in previous chapters, excess heat in the urban areas is mainly derived from the overheating of urban surfaces thus the surface temperature has been selected as measurement of the condition of heat in the assessed urban areas. Due to the sole focus on the urban areas, surface temperatures related to the building surfaces are eliminated. Therefore, the results exclusively present the conditions of remaining space as result of subtraction of building surfaces from the whole urban block. Figure 5.1 shows a sample test representing surface temperatures of an urban block eliminating the building surfaces in black.

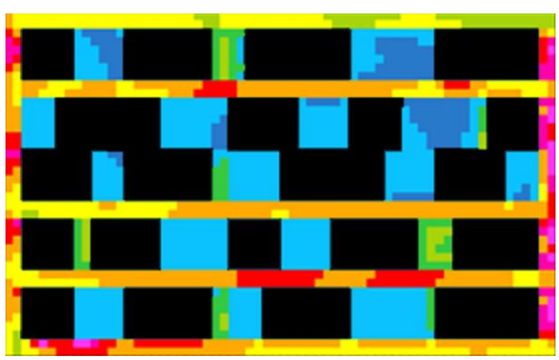


Figure 5.1 Surface temperatures of a sample urban block eliminating the building surface temperatures in black.

Plus, it should be noted that due to the fact that all tests were run only for 24 hours, there is some inconsistency in obtained data during the early hours of simulation run (simulation starts at 6:00). For example, this discontinuity is evident in graphs of Figure 5.3 during 7:00 in summer or during 4:00 to 8:00 in winter. The problem could be solved by running the simulations for 48 hours instead; this allows the ENVI-met software to create consistent flow of data during the second day. Figure 5.2 shows surface temperatures obtained from a model that was run for 48 hours; the graph shows consistency of data during each hour of the day specifically around 4:00 to 8:00. All the tests in this chapter would be re-run again (for 48 hours) to fix this problem for the final submission of the research.

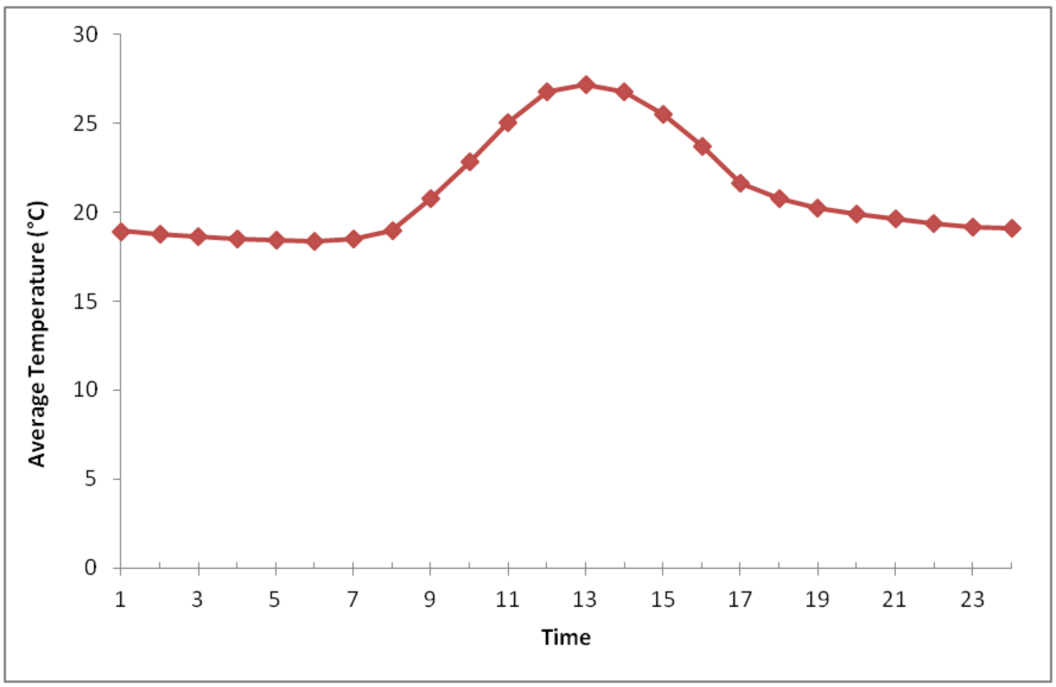


Figure 5.2 Surface temperatures of a simulation that was run for 48 hours.

5.2 Part One : Results and Discussion

This part consists total of 12 different configurations of greenery to be tested, focusing on the effects of three parameters; composition of the green fabric, density of the green fabric and location of grey fabric vs. green fabric. In this section, first the results of tests focusing on each parameter are discussed independently to identify the best strategy that enhances the urban conditions during summer and winter. Second, the results of all tests are compared together in order to identify the “Optimal strategies” with respect to all three parameters. These optimal strategies are implemented in the Part Two of the research which is discussed in later sections.

5.2.1 Composition of Green fabric

Five different tests were designed to study the effect of this parameter. Each of these tests utilizes a certain composition of greenery; table 5.1 shows each test and its corresponding variable under assessment. Trees, grass and green roof are three different types of greenery that are applied in individual configurations.

Table 5. 1 Group of tests and their corresponding variables, investigating parameter 1.

Test	P1
P1-1	Trees and green roof
P1-2	Grass and green roof
P1-3	Trees and grass
P1-4	Grass Only
P1-5	Trees without Grass

Figure 5.3 shows a comparison of the average hourly surface temperatures of a summer and winter day for all the tests in Table 5.1 plus the base test. At first glance, all configurations in both summer and winter fall below the base test, proving the positive effect of applying any type of greenery including grass, trees or green roof in reduction of surface temperatures in urban areas. In addition, different configurations depict diverse behaviors particularly from 9:00 to 17:00 due to the fact that solar radiation increases in these hours of the day. The comparison of summer and winter during peak hours shows that individual configurations may behave differently during

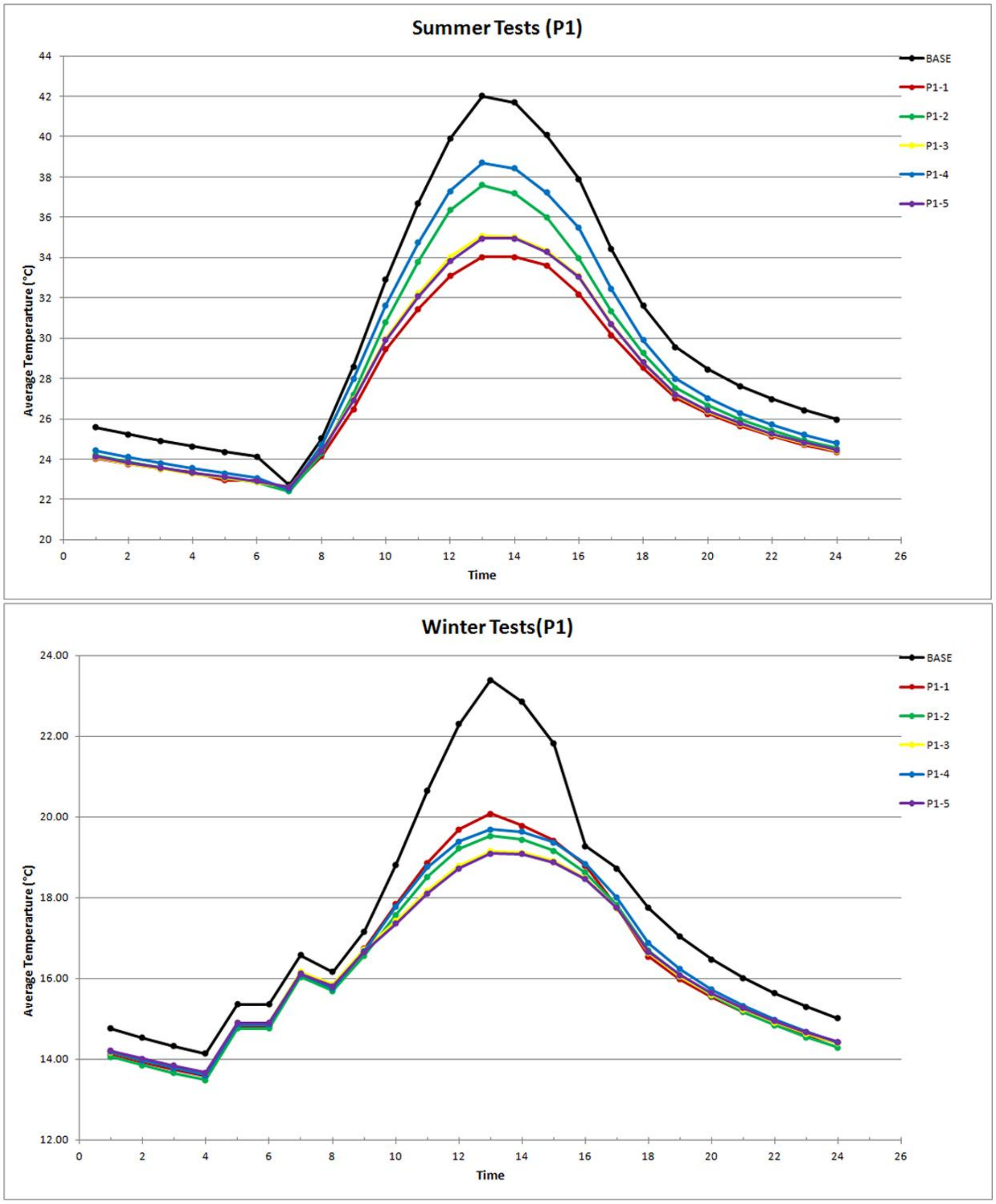


Figure 5.3 Average hourly surface temperatures for tests investigating Composition of Green Fabric vs. Grey Fabric (P1).

each season. For example P1-1 (trees and green roof) results in the least surface temperature during the summer while the same configuration results in the highest surface temperature during the winter. Also, the graphs suggest that the cooling effects of greenery are higher during summer compared to winter. This observation is confirmed in the work of Chang, et al. (2007) and Hamada and Ohta (2010), both researches suggest that urban parks have higher cooling intensity in summer compared to winter and this intensity is higher at noon time compared to night.

Among all the configurations, P1-4 which employs only grass has the highest surface temperature in summer and second highest during winter. This behavior is also evident in the work of Caoa , et al (2010) who concluded that grass has the least effect in reducing surface temperatures compared to trees and shrubs in urban parks. The poor performance of grass is related to its lack of complexity in terms of density and variability of foliage. Zhoua, et al. (2011) who also studied the effect of composition and configuration of greenery, concluded that decrease in land surface temperature is significantly related to complexity, edge density and variability of woody and herbaceous vegetation. Therefore, P1-3 (trees and grass) and P1-5 (Trees without grass) result in reasonably low surface temperatures in both seasons compared to other configurations.

As a result, presence of trees has the most tremendous effects in decreasing the surface temperatures specifically during hot season; this conclusion corresponds to results of Caoa , et al (2010) and Chang, et al. (2007) who suggest that trees have the best cooling effects compared to other forms of greenery. Since low temperatures may not be desired during the winter in some urban areas (due to increasing the need for heating) P1-1 which implements the application of both green roof and trees is selected as the best configuration in terms of Composition of the Green Fabric. Besides, P1-5 which utilizes trees without grass is considered to be the second best configuration during both seasons.

5.2.2 Density of Green Fabric

As discussed in previous chapter, in order to test the effect of density, three different kinds of trees with varying LAD values (representing the plant density) were selected to test the effect of Green Fabric Density. Table 5.2 shows each test and its corresponding variable under assessment.

Table 5.2 Groups of tests and their corresponding variables, investigating parameter 2.

Test	P2
P2-1	Low density (tree with low LAD)
P2-2	Medium Density (tree with medium LAD)
P2-3	High density (tree with high LAD)

Figure 5.4 shows a comparison of the average hourly surface temperatures of a summer and winter day for all the tests in Table 5.2 as well as the base test. Like the previous parameter, different configurations of density depict individual behaviors from 9:00 to 17:00 during the day due to the increased presence of solar radiation. Also, application of greenery with any range of density positively effects the reduction of surface temperatures due to the fact that all cases of density in Figure 5.4 have lower surface temperatures than the base test. Configuration P2-1 which utilizes trees with low LAD values, results in the highest surface temperatures in both summer and winter. P2-2 and P2-3 both result in low surface temperatures in summer and winter featuring trees with medium and high LAD values. Since there is no major difference in the effect of medium and high density trees, medium density trees with medium values of LAD are selected to be the best type of trees that should be utilized in the urban areas.

5.2.3 Relationship of Green Fabric vs. Grey Fabric

In order to test this parameter, 3 different configurations of buildings and greenery were designed and tested. Table 5.3 shows each test and its corresponding variable under assessment for parameter 3.

Figure 5.5 shows a comparison of the average hourly surface temperatures of a summer and winter day for all the tests in Table 5.3 as well as the base test.

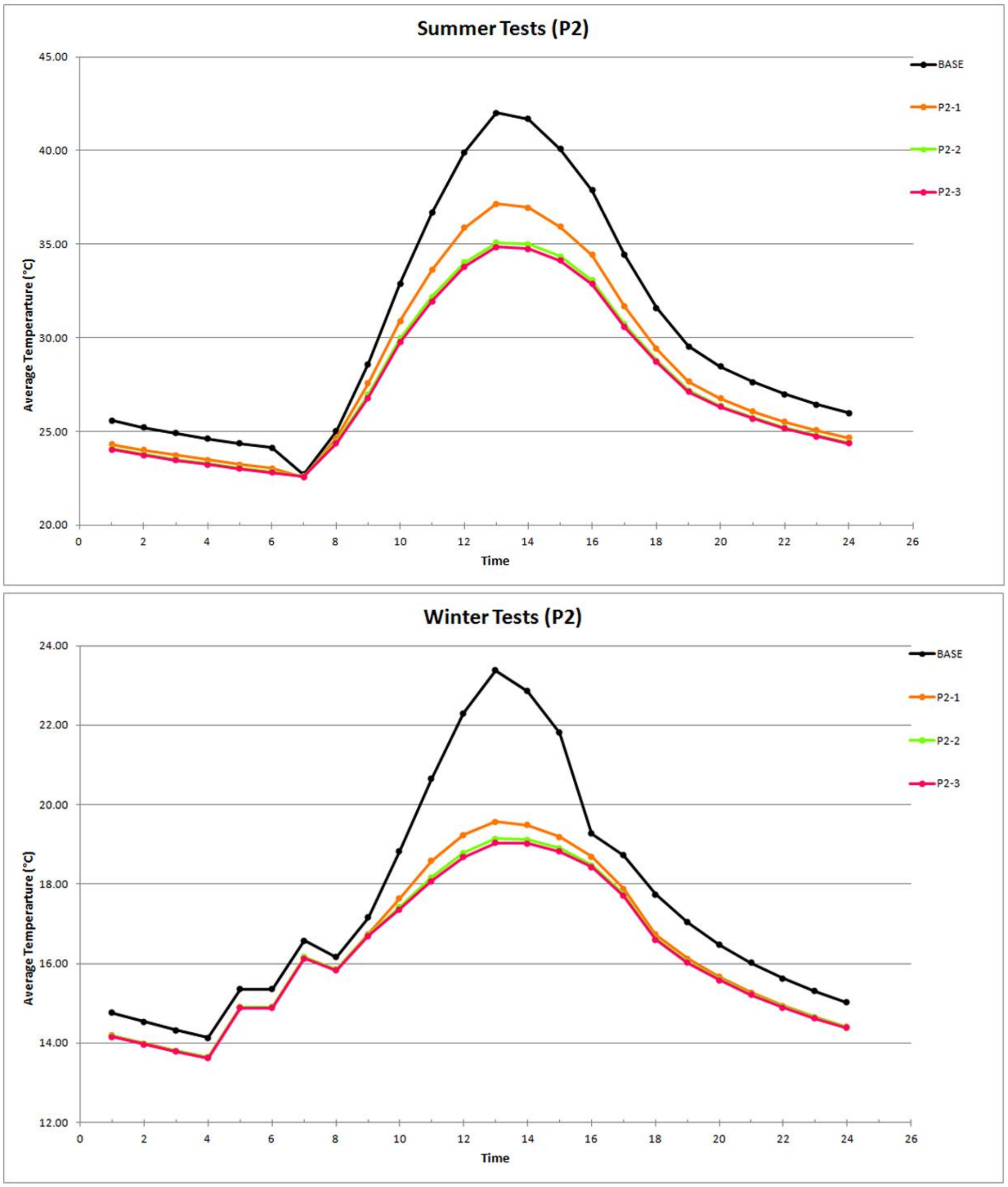


Figure 5.4 Average hourly surface temperatures for tests investigating Density of Green Fabric (P2).

Similar to the other two parameters, location of green vs. grey fabric also positively effects the reduction of surface temperatures in urban areas. These effects are mostly evident from 9:00 to 17:00 due to the increase in amount of solar radiation during these hours of the day. P3-3 which employs the layering of green fabric and grey fabric results in the highest surface temperatures during both summer and winter. However the other two cases behave differently in each season; P3-2 which features centralized grey fabric with surrounding green fabric has the lowest surface temperature during the summer while P3-1 which features centralized green fabric with surrounding grey fabric depicts the lowest surface temperature during the winter.

Table 5.3 Group of tests and their corresponding variables, investigating parameter 3.

Test	P3
P3-1	Centralized green fabric with surrounding gray fabric
P3-2	Centralize gray fabric with surrounding green fabric
P3-3	Layering of grey and green fabric

The cooling effects of greenery in all these cases is related to the compactness of the greenery; layering of greenery features irregular forms of greenery scattered all over the area while both of other configurations feature compact forms of greenery. Caoa , et al. (2010) in their study of cooling effects of parks explain that the compactness of the parks result in better cooling effects while irregular, complex and linear shaped parks contribute less in reduction of heat in urban areas. Due to the fact that low surface temperatures may not be desirable during the winter (due to increasing the need for heating), P3-2 is considered to be the best configuration for the Location of Green Fabric vs. Grey Fabric in the urban areas.

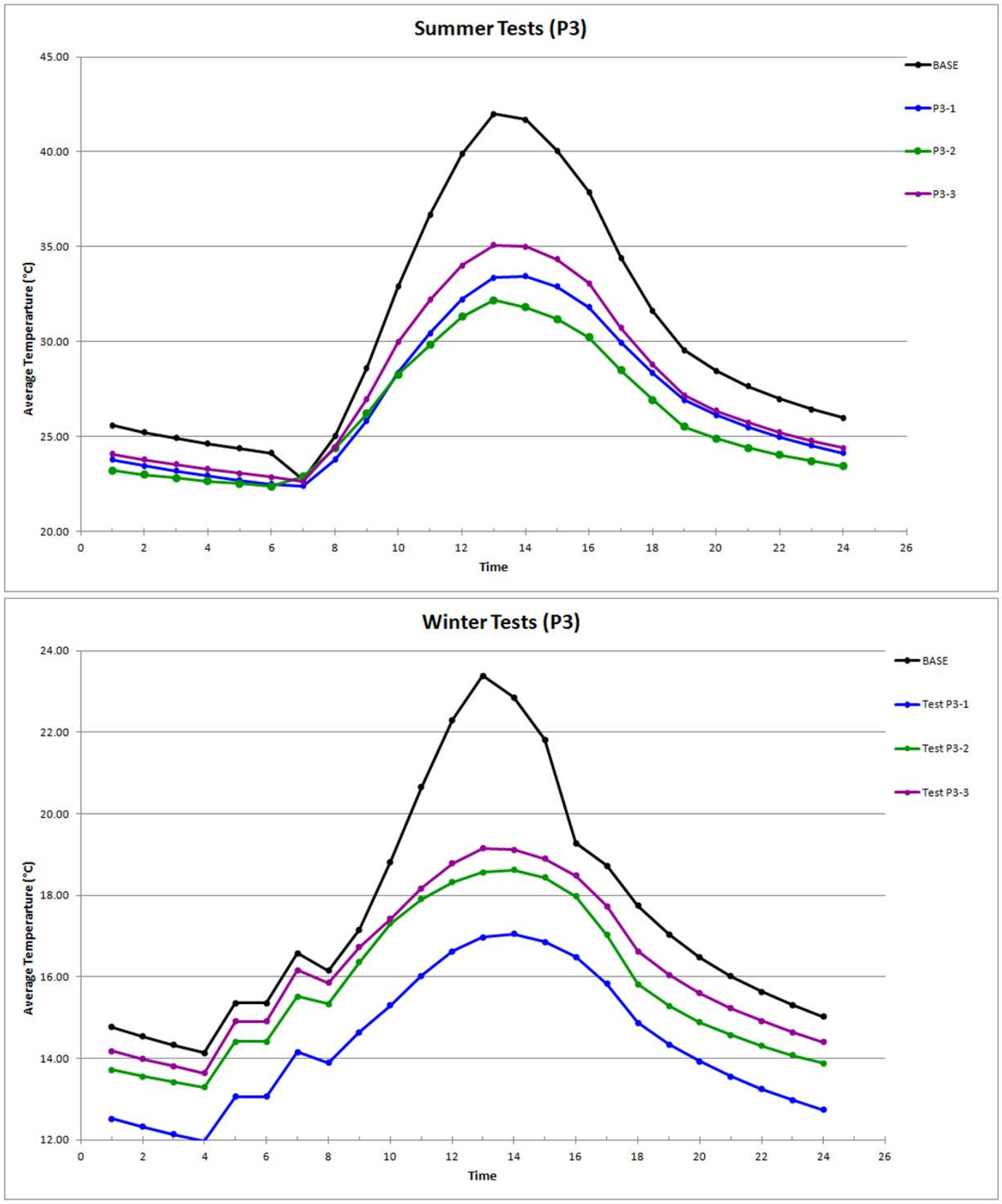


Figure 5.5 Average hourly surface temperatures for tests investigating Location of Grey Fabric vs. Green Fabric (P3).

5.3 Selection of Optimal Strategies

Figure 5.6 shows a comparison of surface temperatures for all tests investigating three parameters. This overall comparison also proves the diverse behavior of individual configurations during the summer and winter; for example P1-1 which features application of trees and green roof results in the highest surface temperatures during the winter while causing reasonable low surface temperatures during summer. Due to this diversity, it is not possible to select only one case among all, and claim it to be the best configuration.

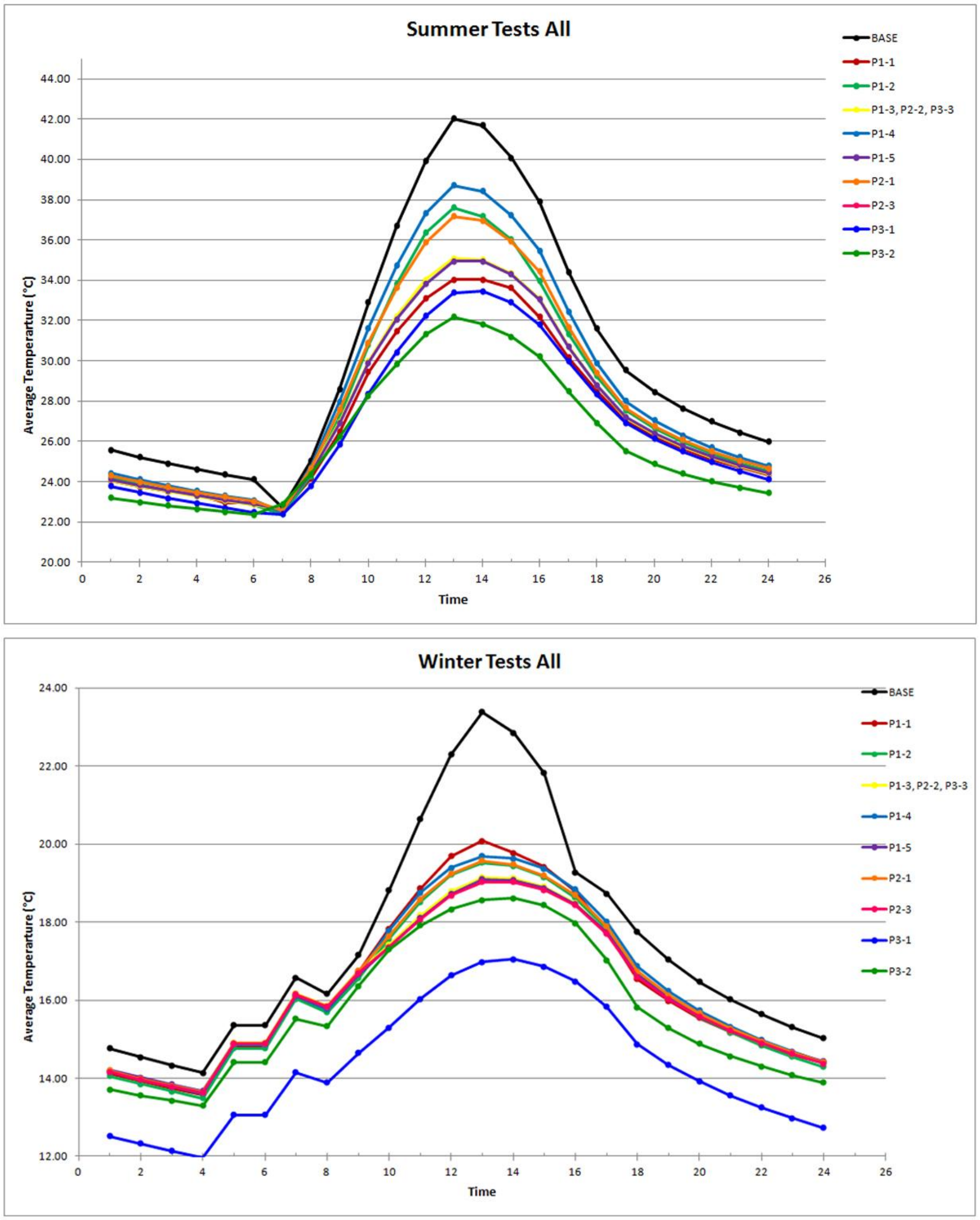


Figure 5.6 Comparison of average hourly surface temperatures for all tests investigating 3 parameters.

Application of each of these strategies in real conditions depends on two factors; first is the performance of the configuration itself which is defined by each of the parameters involved. For example, P3-1 (Centralized green fabric with surrounding gray fabric) and P3-2 (Centralize gray fabric with surrounding green fabric) are considered to be the best configurations during the summer. One could conclude that P3-3 (Layering of grey and green fabric) performs poorly compared to these two conditions however, when other parameters come to play the situation is otherwise; meaning P1-1 which features layering of green and grey fabric, also performs well during summer. This is due to the effect of other parameters, in this case, composition of the green fabric (trees and green roof); therefore it is important to consider the effect of all parameters involved.

The second factor in selecting optimal strategies is the extent to which each strategy could be applicable in real conditions. For example, a dense old urban block in the middle of the city, does not offer enough freedom in applying greenery. Specifically, cases like P3-1 and P3-2 which happen to be the most desirable strategies during summer are not applicable in an urban area with a dense pre-existing fabric of buildings. Hence, based on these two factors, two groups of optimal strategies are selected; first group (Group I) is those strategies that must be considered when designing new urban areas and second group (Group II) is strategies that are applicable in pre-existing urban conditions.

Table 5.4 shows the optimal strategies based on each parameter for both groups of urban areas. When designing new urban areas the best strategy in terms of type and composition of greenery is application of trees without grass. Despite, the results in figure 5.3 that indicate the application of trees and green roof together is the best solution for both summer and winter; it is recommended to go for application of trees without grass due to the fact that this case would eliminate the high expense and maintenance of green roofs in the urban areas. In terms of the density, trees with medium LAD values are recommended since they also result in the same surface temperature as high density trees (Figure 5.4). In terms of the location of green fabric and grey fabric it is highly recommended to employ central grey fabric with surrounding greenery. This strategy is selected because it results in lowest surface temperatures specifically during the summer compared to other two

Table 5.4 Optimal strategies for Group I (new urban areas) and Group II (pre-existing urban areas)

Group of Strategies	Optimal strategy considering P1: Composition of Green Fabric (grass, trees, green roof)	Optimal strategy considering P2: Density of Green Fabric (LAD values of trees)	Optimal strategy considering P3: Location of Grey Fabric vs. Green Fabric
Group I	Trees without grass	Medium Density (tree with medium LAD)	Centralize gray fabric with surrounding green fabric
Group II	Trees and green roof or trees only	Medium Density (tree with medium LAD)	Layering of green fabric and grey fabric

strategies (Figure 5.5); the results of summer conditions are particularly important due to the hot weather of Dubai.

When it comes to selecting the composition of greenery for application in pre-existing urban areas of Dubai, it is recommended to go for either trees or combination of trees and green roof. In certain cases, due to the lack of space for inserting trees in dense urban areas, green roof is also employed to compensate inserting reasonable amount of greenery. Similar to group I, trees with medium values of LAD are also recommended to be utilized in pre-existing urban areas. When it comes to location of greenery, it is very difficult to locate the greenery around the grey fabric or vice versa (Figure 5.5 indicates these two strategies perform better during both seasons). Therefore it is recommended to locate the greenery among the buildings in any space available. The effect of this group of Optimal Strategies is going to be tested in Part Two of the research.

5.4 Part Two

This part of the research aims to test the effect of application of optimal strategies on pre-existing urban conditions in Dubai. As mentioned in Chapter 2, a thermal survey of Dubai in December 2009 showcased existence of urban heat island in older fabric of the city, particularly areas of Deira and Bur Dubai. Therefore, two urban blocks from these two areas were selected for testing the effect of optimal strategies in pre-existing dense urban areas. Figure 5.7 shows the Google Earth images of the selected

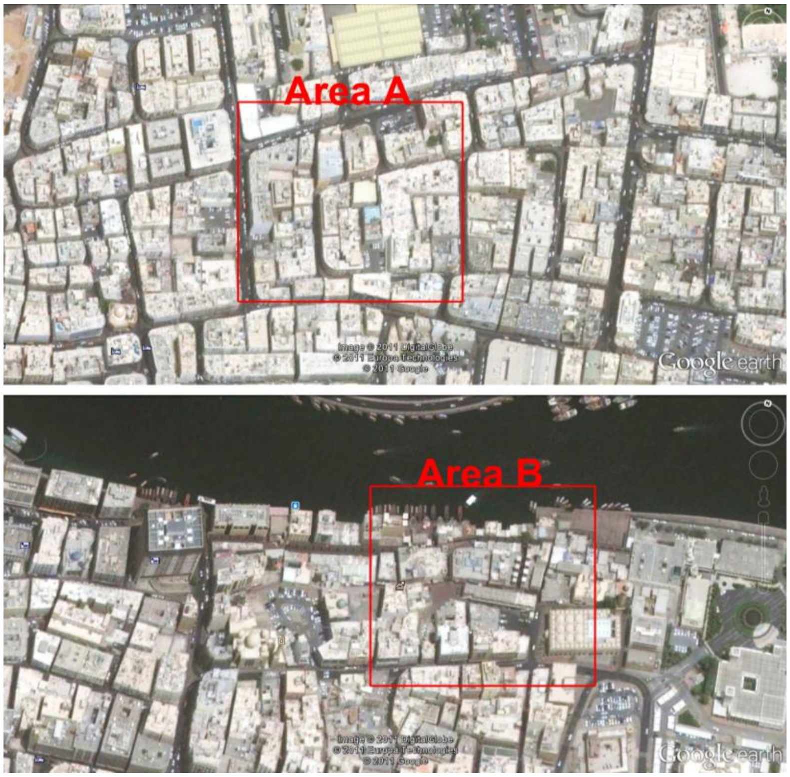


Figure 5.7 Selected urban areas in Dubai for implementing the optimal strategies. (Google Earth)

areas; the selection aims to test the effects of the optimal strategies in two urban locations with different characteristics. Area A is located away from the Dubai Creek to test the effects in a relatively dry urban location while Area B is located along the coast of Dubai Creek to test the effect of the strategies in a more humid urban context. Both selections encompass an area of 150m x 75m with medium height buildings (4 stories). Also both locations lack urban vegetation and any empty spot is either covered in sand or asphalt.

5.4.1 Model Setup

After selecting the areas, ENVI-met models were developed for both selections (Figure 5.8). The input configurations of these models are similar

Figure 5.8 Figure 5.8 ENVI-met models of the selected urban areas.

to those of the Part One of the research, which were explained in detail during Chapter 4. Similar to Part One, the models were tested in two seasons of summer and winter to see the effect of the strategies during both hot and cold weather conditions. Each model is tested in 3 different configurations; the first configuration is the existing situation without any alteration. The second configuration is addition of trees of medium LAD values to all the empty areas as well as along the roads (Figure 5.9). The third configuration features addition of green roof besides inserting trees in all the empty spots. It should be noted that these configurations were developed based on selected Optimal Strategies for pre-existing urban areas in section 5.2.

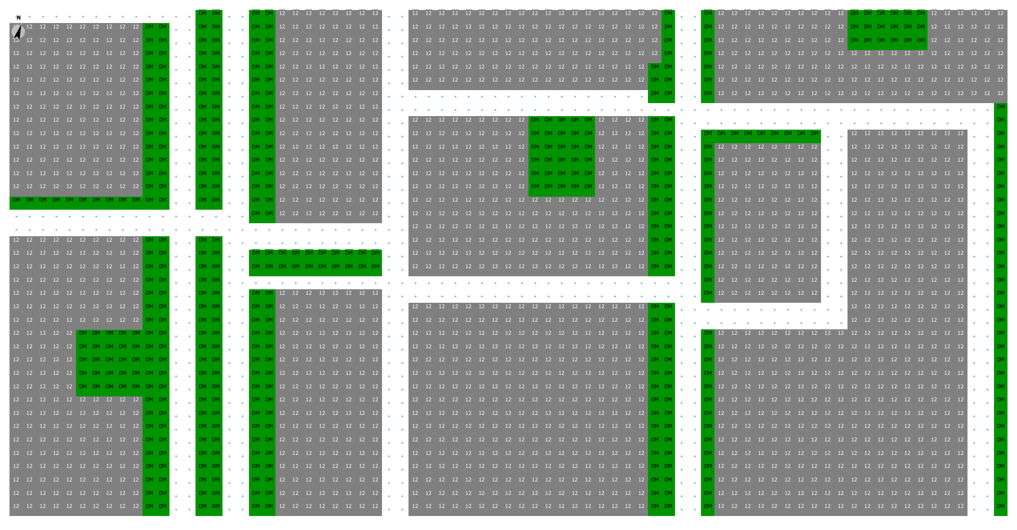
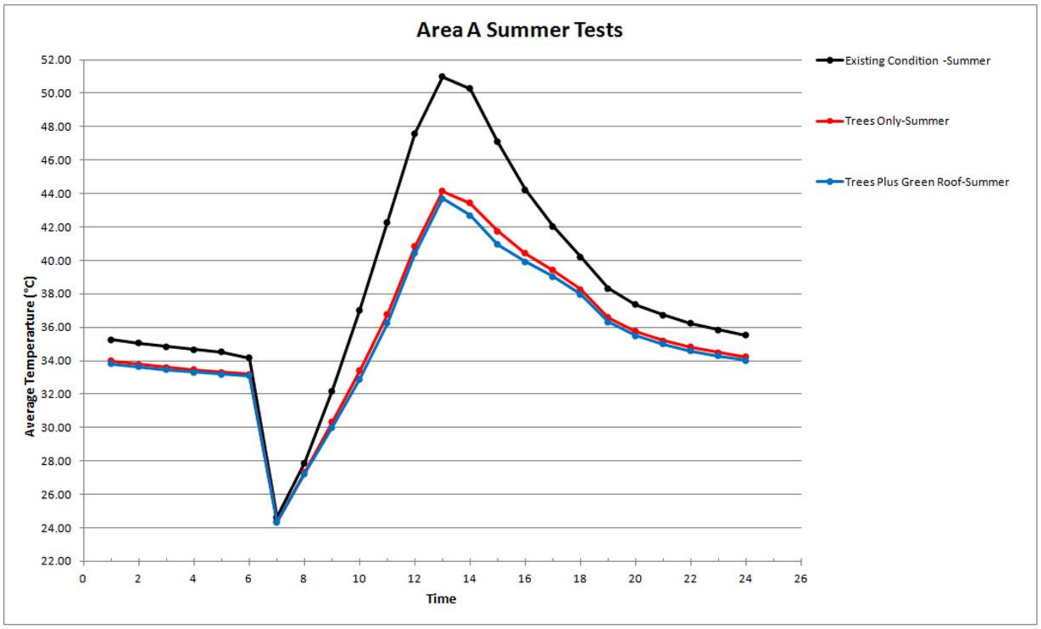


Figure 5.9 ENIV-met model of Area A after inserting trees in empty spaces.

5.4.2 Results and Discussion

Similar to the results of Part One, the data related to the buildings were eliminated to better understand the effect of the strategies in the urban areas. Average hourly surface temperatures were extracted and processed for further analysis and comparison in this part of the research as well.

Figure 5.10 showcases the results of three configurations that were tested on Area A (urban area away from Dubai Creek) during summer and winter. Based on the figures, inserting greenery in this area has a tremendous effect on reducing surface temperatures during both seasons. Different conditions showcase individual behavior specifically from 9:00 to 17:00 due to the abundance of solar radiation during these hours. Even though, the strategy of inserting both trees and green roofs seems to result in the lowest surface



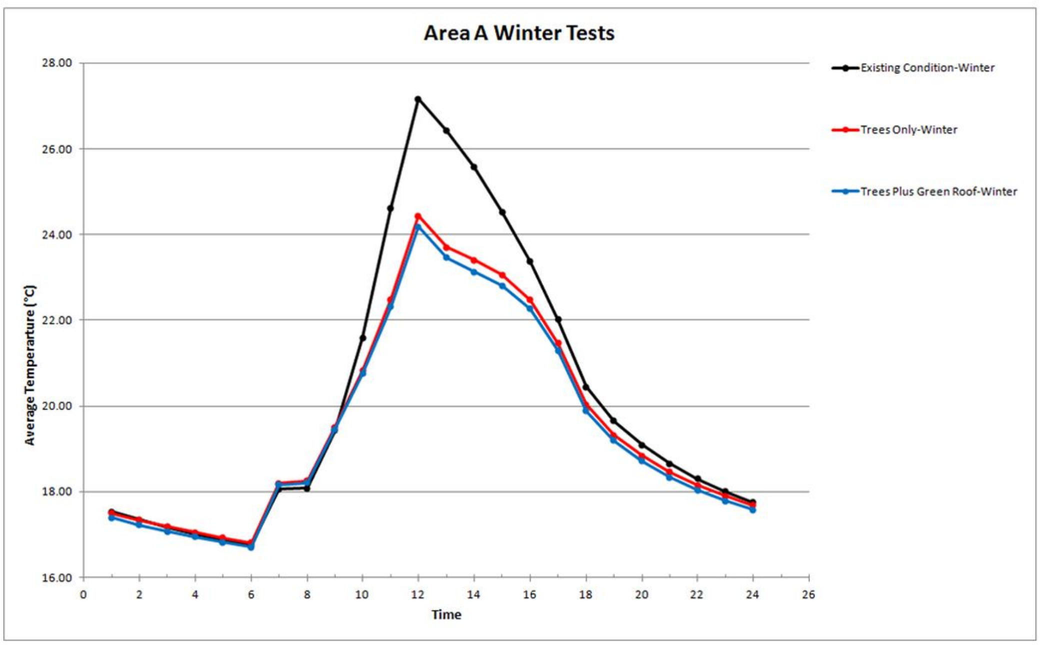


Figure 5.10 Average hourly surface temperatures for different tests investigating the effects of Optimal Strategies in Area A (area away from Dubai Creek).

temperatures, the configuration of inserting only trees is considered to be the best configuration. The fact that the case of Trees only, and Trees plus Green roof obtain close results indicates that green roofs have negligible effect on reducing surface temperatures in the urban areas.

Figure 5.11 also shows the average surface temperatures obtained from

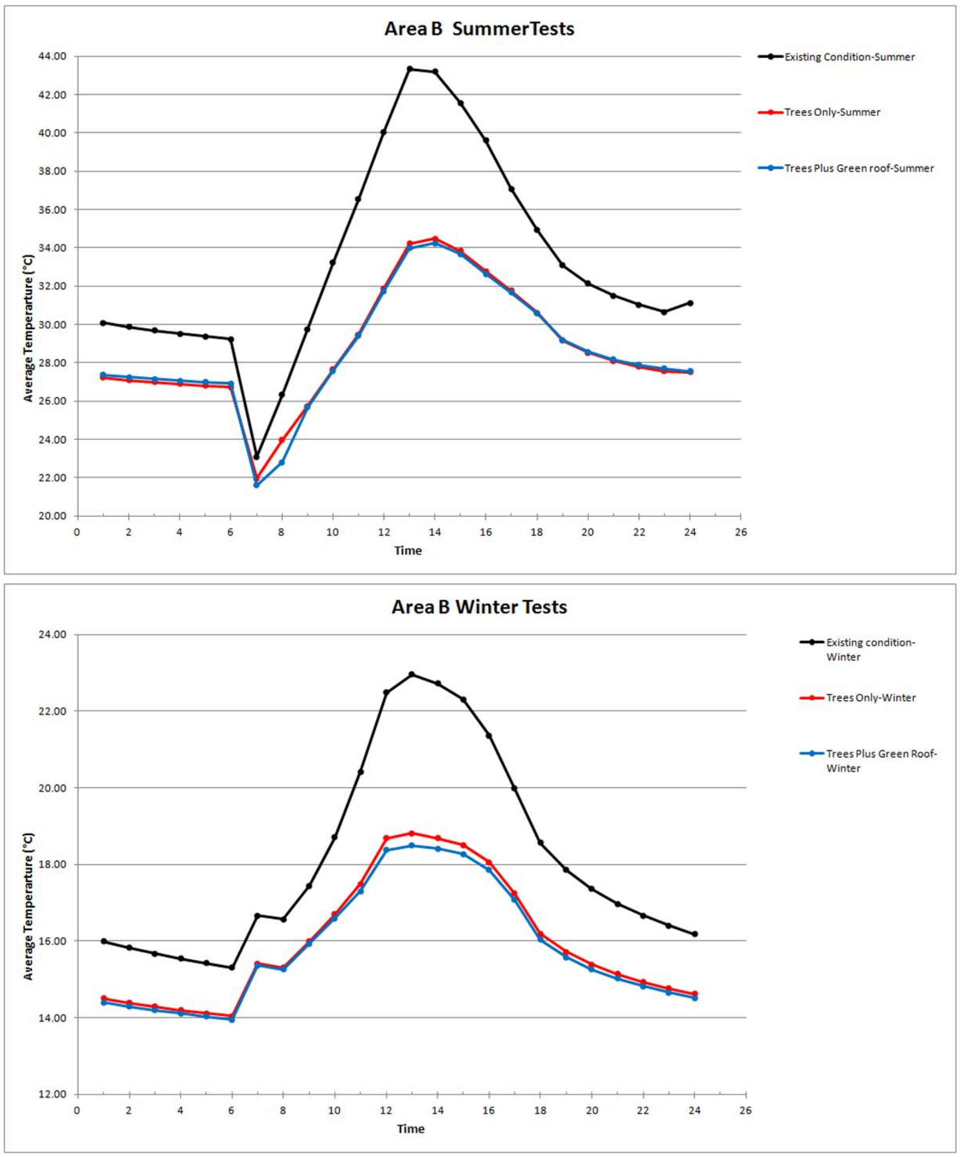


Figure 5.11 Average hourly surface temperatures for different tests investigating the effects of Optimal Strategies in Area B (area close to Dubai Creek).

tests in Area B. The trends in this area are very close to Area A; inserting greenery results in reduction of surface temperatures during both seasons. Also inserting green roof besides trees seems to have negligible effects on reducing surface temperatures.

Chen et al. (2002) measured the cooling effect of green roof on ambient temperatures and confirmed that this cooling effect is restricted by distance from the green roof; for example air temperatures measured at 1m above the green roof were considerably lower than those measured at 300mm above the green roof. Since the data only represents surface temperatures of areas around the buildings, which are at significant distance from the green roofs, this observation proves the negligible effect of green roof in reducing surface temperatures in both Area A and B. Also looking at the results of both Areas, a tremendous temperature difference exists between the current condition and conditions after inserting greenery. This enormous difference is explained by the fact that, currently all surfaces in both areas are covered in asphalt or concrete. These materials massively contribute to the increase of surface temperatures in the urban areas as a result of their properties. This behavior of hard materials is studied in the work of Wong, et al. (2007) too; they tested the effect of greenery on a campus by removing all the trees in the area and replacing them by buildings. This scenario also resulted in extremely high surface temperatures similar to current conditions of Area A and B.

Looking at the results of both areas, all configurations showcase the maximum difference in value right after the noon time during 13:00 h. In order to see the distribution of temperatures during this peak hour, the map of surface temperatures for the existing condition and condition of adding tress only, for Area A are compared in figure 5.12. These thermal maps indicate the tremendous reduction of surface temperatures in areas directly adjacent to places where trees are inserted (a). Also in areas were no trees were inserted directly (b), there is evidence of reduction in surface temperature.

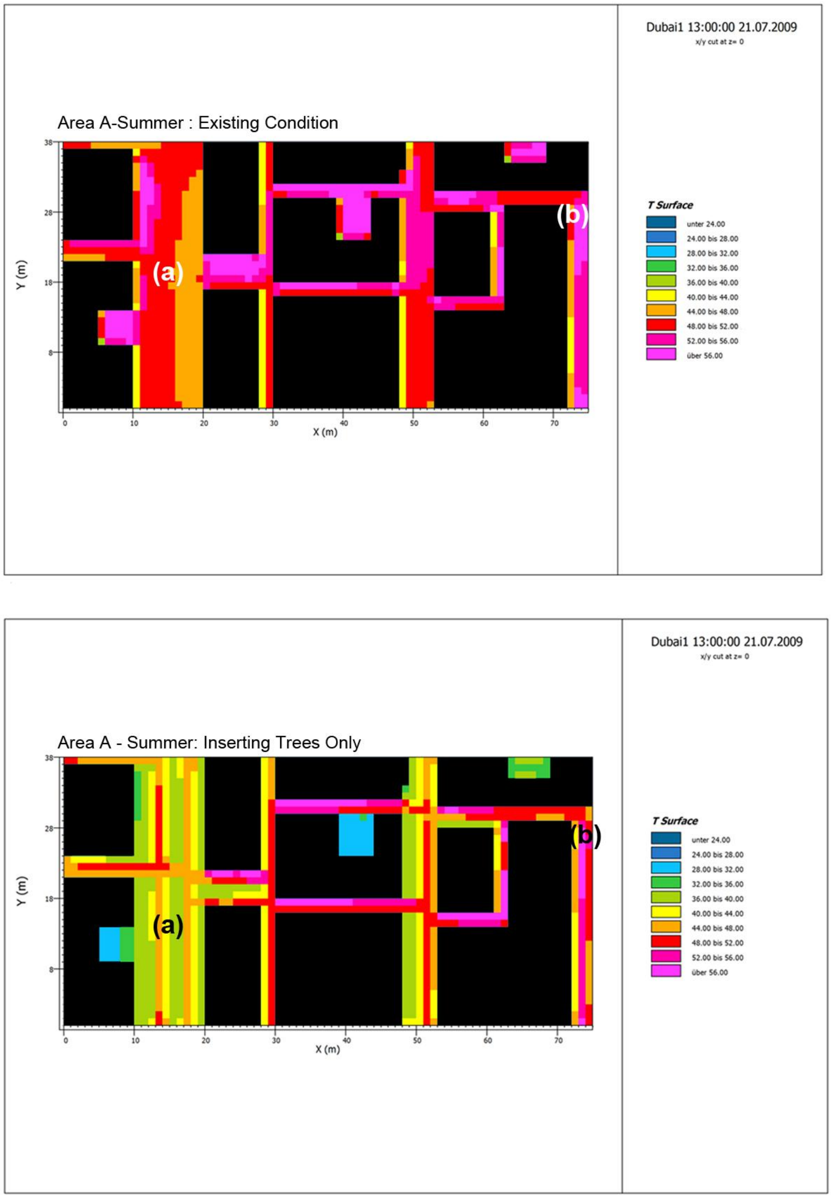


Figure 5.12 Thermal map of Surface temperatures for different configurations in Area A at 13:00 on a summer day.

CHAPTER 6

Conclusion and Recommendations

6.1 Conclusion

The main focus of this research was on the effect of greenery on reduction of excess heat in the urban areas of Dubai. In order to study this effect, three parameters including, composition of green fabric (grass, trees, green roof), density of green fabric (LAD values of trees) and location of green fabric vs. grey fabric were selected for further investigations. 12 tests were developed each featuring a different configuration and focus on all three parameters; the results were interpreted based on average hourly surface temperatures of areas around the buildings (data from the buildings were eliminated). Two groups of Optimal Strategies were selected for application in real conditions; Group I consisted of strategies that should be applied when designing new urban areas. These strategies include utilizing only trees with medium LAD value (density of foliage) and applying centralized grey fabric and surrounding greenery. Group II consisted of strategies that should be applied in pre-existing conditions including application of trees only or trees with green roof, application of medium LAD value trees and layering of green fabric and grey fabric. The second group of Optimal Strategies were tested on two different urban areas; one located away from Dubai Creek and the other located along the coast of Dubai Creek.

The results from both parts of the research revealed that in terms of composition of greenery, trees have the best contribution in reduction of surface temperatures in the urban areas of Dubai. On the other hand, grass has the least contribution in reduction of urban heat due to the lack of complexity and variation in foliage. Also green roofs were proved to perform poorly in reducing the surface temperatures in urban areas; this is due to the fact that the cooling effects of green roofs reduces by distance and therefore this effect is negligible on the overall temperature reduction in urban areas. It should be noted that this observation is only true at the macro scale and it does not contradict the other benefits of green roofs at the micro scale which were out of the scope of this research.

In terms of the density of the trees, it is concluded that trees with medium values of LAD perform the best in terms of reducing surface temperatures. On the other hand, trees with low values of LAD perform poorly in reducing surface temperatures. When it comes to location of green fabric vs. grey fabric, it is concluded that placing greenery in compact form around the buildings or in the middle of buildings performs better in reducing surface temperatures. On the other hand, placing greenery in scattered irregular forms among buildings does not perform very well compared to compact cases. The conclusion of this research signifies the importance of greenery in reducing excess heat and creating balanced microclimatic conditions in urban areas.

6.2 Recommendations

When designing new urban areas, it is recommended to avoid designing building dominated master plans. Designers should always keep in mind the importance of green fabric in creating balanced and healthy microclimates in urban areas. Designers should specify trees with medium LAD values as the main type of greenery in new urban areas. It is also recommended to design the urban greenery in compacted forms around the cluster of buildings and avoid inserting scattered greenery among buildings in irregular forms. It is also recommended to avoid designing grass covered areas due to the fact that grass has negligible effect on reducing excess heat in urban areas besides requiring high maintenance and cost. Designers should consider the fact that green roofs have minimal effect on reducing surface temperatures in urban areas and utilizing green roofs is only justifiable through other benefits which were not the scope of this research.

On the other hand, when employing strategies for enhancement of existing urban areas, it is also recommended to insert medium LAD trees as the main type of greenery. Designers should always aim for inserting greenery as compact as possible in pre-existing conditions. In this case, parking lots, wide pedestrian paths or roads offer adequate space to insert trees in compact forms. Similar to the case of designing new areas, it is important to note that inserting green roofs and grass does not provide significant means of reducing surface temperatures in urban areas. In general it is recommended to aim for minimizing the bare concrete and asphalt surfaces when applying strategies for reducing surface temperatures in urban areas.

6.3 Further Research

The outcomes of leads to further possible areas of research in this field; some of these possibilities are:

- exploring the effects of other types of greenery such as hedges and vertical greenery including green walls and green facades on reducing the surface temperatures in urban areas
- investigating the effects of greenery on variables such as air temperature, wind speed and direction, humidity, heat and energy
- testing the optimal strategies on more pre-existing/newly designed urban areas with different sizes, land use, building characteristics and microclimatic conditions
- studies on identifying the most efficient types of trees suitable for urban areas of Dubai; specifying indigenous trees in Dubai that feature medium values of LAD; explore the water requirements and cost of maintenance of different species of trees
- exploring the effect of Optimal Strategies on both newly designed and pre-existing urban areas in terms of their required costs and maintenance as well as their benefits in terms of energy savings and comfort levels
- Carrying Field studies on urban areas of Dubai that feature Optimal Strategies; comparing field study results with the findings of this

research in order to clarify the effects of the strategies in real conditions

- Investigating the effects of greenery along with other mitigation strategies of Urban Heat Islands such as modifying building materials and building geometry in the old fabric of Dubai; this investigation would predict the extent to which urban heat island is preventable in the old dense areas of Dubai

References

Alexandri, E. and Jones, P. (2008) Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates, *Building and Environment,* 43(7), p.480-493.

ASHRAE Standing Standard Project Committee (2004). *ASHRAEE Standard: Energy Standard for*. New York: ASHRAE.

Avissar, R. (1994) Potential effects of Vegetation on the urban thermal environment, *Atmospheric Enviroment,*30(3), p.437-448.

Ayata, T. et al. (2011) An investigation of sensible heat fluxes at a green roof in a laboratory setup, *Building and Environment,* 46(3), p.1851e1861.

Bornstein, R. (1968) Observations of the Urban Heat Island effect in New York city, *Journal of Applied Meterology,* 7(7), p.575-582.

Caoa, X. et al. (2010) Quantifying the cool island intensity of urban parks using ASTER and IKONOS data, *Landscape and Urban Planning,*96(5), p.224–231.

Chang, C. et al. (2007) A preliminary study on the local cool-island intensity of Taipei city parks, *Landscape and Urban Planning,* 80(4), p.386-395.

Chen, Y. et al. (2002) Investigation of thermal bene#ts of rooftop garden in the tropical environment, *Building and Environment,* 38(6), p.261-270.

Cheng, C. et al. (2010) Thermal performance of a vegetated cladding system on facade walls, *Building and Environment,* 45(6), p.1779-1787.

Dutt, A.K (2003). *Challenges to Asian urbanization in the 21st century*. USA: Springer.

Earth observatory (2009) *Urbanization of DubaiPosted April 29, 2009 ,* [online] Available at: http://earthobservatory.nasa.gov/IOTD/view.php?id=38344 [Accessed: 5th of May 2011].

Edward, N. et al. (2011) A study on the cooling effects of greening in a high-density city: An experience from Hong Kong, *Building and Environment,* doi: 10.1016/j.buildenv.2011.07.014

Eliasson, I**.** (1995) Urban Nocturnal Temperatures, Street Geometry and Land Use, *Atmospheric Environmenr,* 30(3), p.379-392

Envi-met (2004) *Envi-met Start page,* [online] Available at: http://www.envi-met.com/ [Accessed: 8th Aug 2011].

Fahmy, M. and Sharples, S. (2009) On the development of an urban passive thermal comfort system in Cairo, Egypt, *Building and Environment,*44(3), p.1907–1916.

Fahmy, M. et al. (2010) LAI based trees selection for mid latitude urban developments: A microclimatic study in Cairo, Egypt, *Building and Environment,* 45(2), p.345–357.

Fioretti, R. et al. (2010) Green roof energy and water related performance in the Mediterranean climate , *Building and Environment,* 45(8), p.1890-1904.

Gartland,L (2008). *Heat islands: understanding and mitigating heat in urban areas*. UK: Earthscan.

Georgi, J. and Dimitriou, D. (2010) The contribution of urban green spaces to the improvement of environment in cities: Case study of Chania, Greece, *Building and Environment,*45(6), p.1401-1414.

Giridharan, R. et al. (2007) Lowering the outdoor temperature in high-rise high-density residential developments of coastal Hong Kong: The vegetation influence, *Building and Environment,* 43(9), p.1583–1595.

Gomez, F. (1998) Vegetation and climatic changes in a city, *Ecological Engineering,* 10(4), p.355-360.

Hamada, h. and Ohta , T. (2010) Seasonal variations in the cooling effect of urban green areas on surrounding , *urban forestry and urban greening,* 9(5), p.15-24.

Hanaki, K. (2008) *Urban environmental management and technology,* Tokyo: Springer, p.224-230.

Hardoy, J (1992). *Environmental problems in Third World cities*. UK: Earthscan. 37-60.

Howard, L (1833). *The climate of London: deduced from meteorological observations made in the metropolis and at various places around it*. London: Harvey and Darton, J. and A. Arch, Longman, Hatchard, S. Highley [and] R. Hunter.

IEA Statistics . (2007). *World Energy Use Per Capita.* Available: http://www.iea.org/stats/index.asp. Last accessed 9th Mar 2011.

Ihara, T. et al. (2008) City-block-scale sensitivity of electricity consumption to air temperature and air humidity in business districts of Tokyo, Japan,*Energy ,* 33(2), p.1634–1645.

Jim, C. and Hongming, H. (2010) Estimating heat flux transmission of vertical greenery ecosystem, *Ecological Engineering,* 27(3), p.120-131.

Kolokotroni, M. and Giridharan, R. (2008) Urban heat island intensity in London: An investigation of the impact of physical characteristics on changes in outdoor air temperature during summer, *Solar Energy,* 82, p.986–998

Krüger, E. et al. (2011) Impact of urban geometry on outdoor thermal comfort and air quality from field measurements in Curitiba, Brazil, *Building and Environment,* 46(4), p.621-634.

Marcotullio, P & McGranahan, G (2007). *Scaling urban environmental challenges: from local to global and back*. USA: Earthscan.

Priyadarsini, R. et al. (2008) Microclimatic modeling of the urban thermal environment of Singapore to mitigate urban heat island, *Solar Energy,*82(2), p.727-745.

Quattrochi, D. (1998) Analysis of vegetation within a semi-arid urban environment using high spatial resolution airborne thermal infrared remote sensing data, *Atmospheric Environment,* 32(1), p.19-33

Saaroni, H. et al. (2000) Spatial distribution and microscale characteristics of the urban heat island in Tel-Aviv, Israel, *Landscape and Urban Planning,* 48(2), p.1-18

Santamouris, M. et al. (2007) On the development, optical properties and thermal performance of cool colored coatings for the urban environment, *Solar Energy,* 81(5), p.488–497.

Shashua-Bar, L. and Hoffman, M. (2003) Quantitative evaluation of passive cooling of the UCL microclimate in hot regions in summer, case study: urban, *Building and Environment,* 39(9), p.1087-1099.

Stabler, L. et al. (2005) Microclimates in a desert city were related to land use and vegetation index, *Urban Forestry & Urban Greening,* 3(2), p.137-147.

Susca, T. et al. (2011) Positive effects of vegetation: Urban heat island and green roofs,*Environmental pollution,* 159(6), p.1700-1708.

Synnefa, A. (2011) Experimental testing of cool colored thin layer asphalt and estimation of its potential to improve the urban microclimate, *Building and Environment,* 46(6), p.38-44.

Synnefa, A. et al. (2008) A study of the thermal performance of reflective coatings for the urban environment, *Solar Energy,* 80(3), p.968-981.

Takebayashi, H. and Moriyama, M. (2009) Study on the urban heat island mitigation effect achieved by converting to grass-covered parking, *solar energy,* 83(4), p.1211–1223.

Tan, A. et al. (2009) Energy simulation of vertical greenery systems, *Energy and Buildings,* 41(9), p.1401–1408.

United Nations. Dept. of Economic and Social Affairs. Population Division (2004). *World urbanization prospects: the 2003 revision*. United Nations: United Nations Publications. 12-15.

United Nations. Dept. of Economic and Social Affairs. Population Division. (2006). *World Population Prospects: The 2006 Revision and World Urbanization Prospects: The 2007 Revision*. Available: http://esa.un.org/unup/. Last accessed 8th Feb 2011.

Voiland, A. (2010). *Satellites Pinpoint Drivers of Urban Heat Islands in the Northeast*. Available: http://www.nasa.gov/topics/earth/features/heat-island-sprawl.html#. Last accessed 9th Mar 2011.

Wang, S (2000). *Handbook of Air Conditioning and Refrigeration* . 2nd ed. New York: McGraw-Hill Professional Publishing. 89-90

Wanphen, S. and Nagano, K. (2009) Experimental study of the performance of porous materials to moderate the roof surface temperature by its evaporative cooling effect ,*Building and Environment,* 22(2), p.338-351.

Won, N. and Yu, C. (2005) Study of green areas and urban heat island in a tropical city, *habitat international,* 29(7), p.547-558.

Wong, N. and Jusuf, S. (2008) GIS-based greenery evaluation on campus master plan,*Landscape and Urban Planning,* 84(7), p.166-182

Wong, N. et al. (2007) Environmental study of the impact of greenery in an institutional campus in tropics , *Building and Enviroment,* 42(8), p.2949–2970.

Wong, N. et al. (2010) Thermal evaluation of vertical greenery systems for building walls, *Building and Environment,* 45(8), p.663–672.

Yu, C. and Wong, N. (2006) Thermal benefits of city parks, *Energy and Buildings,* 38(2), p.105-120.

Zacarias, N. (2011) *Interview on Urban Heat Island Survey in Dubai*. Interviewed by Tahereh Rajabi [in person], Dubai Municipality Environment section, 10th February 2011.

Zhanga, X. et al. (2010) Relationship between vegetation greenness and urban heat island effect in Beijing City of China, *Procedia Environmental Sciences,* 2(5), p.438–1450.

Zhoua, W. et al. (2011) Does spatial configuration matter?Understanding the effects of land cover pattern on land surface temperature in urban landscapes, *Landscape and Urban Planning,* 96(2), p.65-76.

Appendices

Appendix A Samples of Extracted Data Manipulation – remaining files available in soft copy

Figure A. 1: Data for Green Roof in Area B during the Winter at 10 AM

	A	B	C	D	E
1	x(m)	y(m)	Temprature (K)	Temprature (˚C)	Average Temprature (˚C)
2	1	91	286.51	13.51	16.60
3	1	89	286.51	13.51	
4	1	87	286.52	13.52	
3431	149	77	286.95	13.95	
3432	149	75	288.39	15.39	
3433	149	73	287.16	14.16	
3434	149	57	291.17	18.17	
3435	149	55	298.31	25.31	
3436	149	53	292.62	19.62	
3437	149	15	302.15	29.15	
3438	149	13	301.08	28.08	
3439	149	11	300.25	27.25	
3440	149	9	299.67	26.67	
3441	149	7	299.49	26.49	
3442	149	5	299.48	26.48	
3450	149	3	299.42	26.42	
3451	149	1	299.35	26.35	
3452					

Figure A.2 Data for Green Roof in Area B during the Winter at 10 AM

	A	B	C	D	E
1	x(m)	y(m)	Temprature (	Temprature (˚C)	Average Temprature (˚C)
2	1	75	311.27	38.27	36.58
3	3	75	310.99	37.99	
4	5	75	310.83	37.83	
2793	33	1	309.87	36.87	
2794	35	1	309.90	36.90	
2795	37	1	309.64	36.64	
2796	39	1	309.59	36.59	
2805	57	1	309.50	36.50	
2806	59	1	309.48	36.48	
2825	97	1	308.83	35.83	
2826	99	1	308.89	35.89	
2827	101	1	309.60	36.60	
2828	103	1	309.54	36.54	
2829	105	1	309.00	36.00	
2849	145	1	310.58	37.58	
2850	147	1	310.64	37.64	
2851	149	1	309.59	36.59	
2852					

Figure A.3 Data for Green in Area A during the Summer at 7 PM

Appendix B Tabulated simulation results for all tests performed in Part One of the research showing Average Surface Temperatures of urban areas excluding buildings.

Table B. 1: Summary of Average Temperature (˚C) for Summer Tests-P1

Time	BASE	P1-1	P1-2	P1-3	P1-4	P1-5
1	25.57	24.03	24.18	24.07	24.43	24.12
2	25.22	23.75	23.87	23.78	24.10	23.83
3	24.90	23.52	23.58	23.52	23.81	23.56
4	24.62	23.37	23.32	23.28	23.54	23.32
5	24.36	22.96	23.08	23.06	23.30	23.10
6	24.12	22.96	22.86	22.85	23.07	22.90
7	22.71	22.54	22.39	22.60	22.48	22.60
8	25.01	24.16	24.29	24.44	24.71	24.41
9	28.60	26.47	27.20	26.96	27.97	26.91
10	32.89	29.44	30.79	29.97	31.63	29.91
11	36.68	31.45	33.80	32.20	34.73	32.06
12	39.90	33.09	36.35	34.02	37.30	33.82
13	42.01	34.03	37.60	35.09	38.70	34.95
14	41.68	34.02	37.17	35.01	38.42	34.94
15	40.07	33.61	36.01	34.34	37.22	34.29
16	37.88	32.17	33.96	33.08	35.47	33.04
17	34.41	30.16	31.33	30.71	32.44	30.68
18	31.60	28.52	29.25	28.79	29.90	28.79
19	29.55	27.02	27.54	27.18	28.00	27.22
20	28.45	26.25	26.65	26.36	27.03	26.40
21	27.64	25.64	25.97	25.73	26.30	25.77
22	26.98	25.13	25.41	25.21	25.71	25.26
23	26.44	24.70	24.94	24.78	25.22	24.83
24	25.97	24.35	24.54	24.40	24.79	24.45

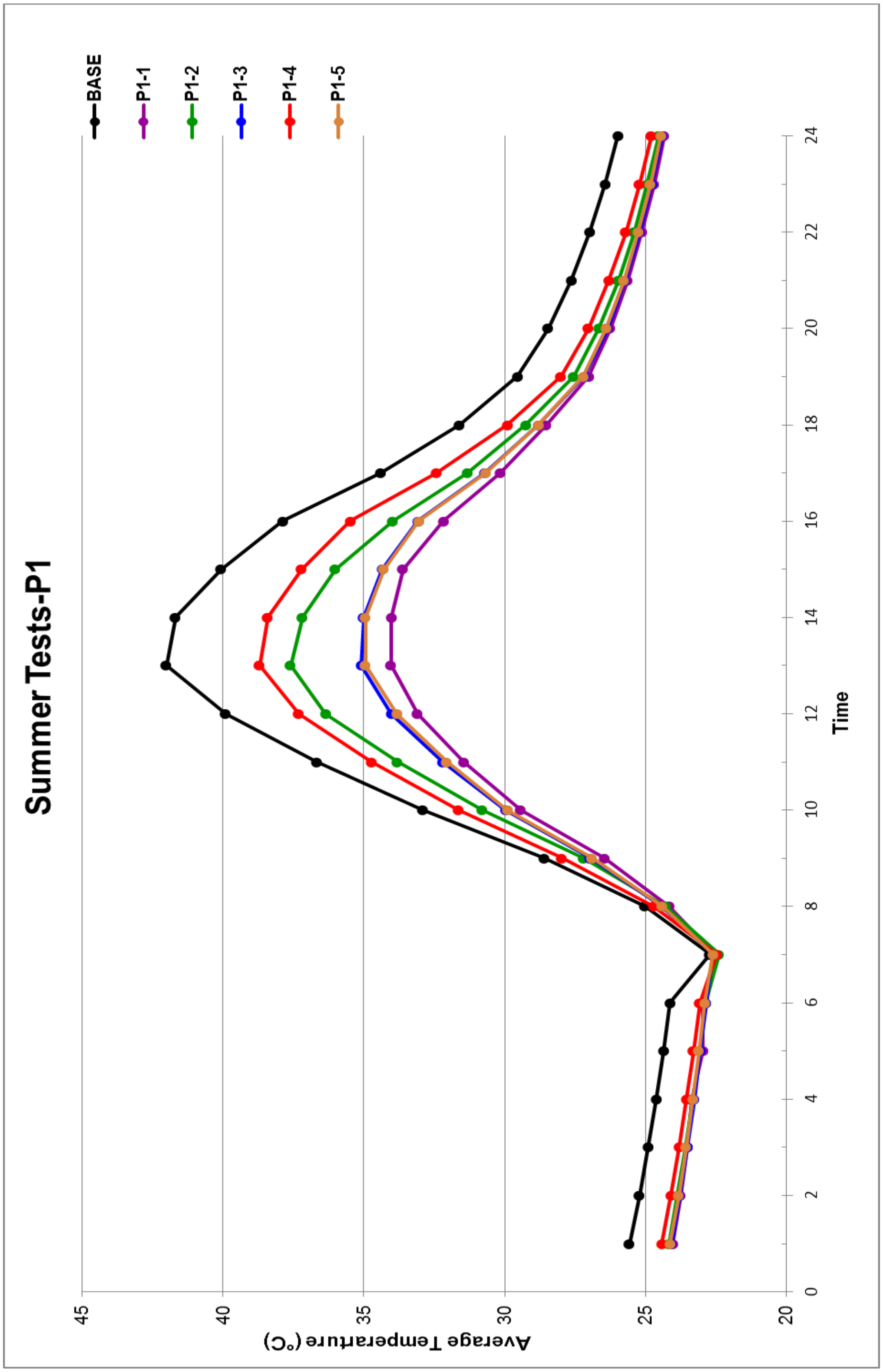


Figure B. 1: Average Temperature for Summer Test-P1

Table B. 2: Summary of Average Temperature (˚C) for Summer Tests-P2

Time	BASE	P2-1	P2-2	P2-3
1	25.57	24.31	24.07	24.02
2	25.22	24.00	23.78	23.73
3	24.90	23.72	23.52	23.46
4	24.62	23.47	23.28	23.22
5	24.36	23.24	23.06	23.00
6	24.12	23.03	22.85	22.79
7	22.71	22.56	22.60	22.57
8	25.01	24.63	24.44	24.34
9	28.60	27.56	26.96	26.78
10	32.89	30.90	29.97	29.77
11	36.68	33.63	32.20	31.95
12	39.90	35.87	34.02	33.79
13	42.01	37.16	35.09	34.84
14	41.68	36.95	35.01	34.75
15	40.07	35.94	34.34	34.12
16	37.88	34.43	33.08	32.86
17	34.41	31.68	30.71	30.56
18	31.60	29.42	28.79	28.71
19	29.55	27.66	27.18	27.12
20	28.45	26.75	26.36	26.31
21	27.64	26.07	25.73	25.68
22	26.98	25.52	25.21	25.17
23	26.44	25.05	24.78	24.73
24	25.97	24.66	24.40	24.36

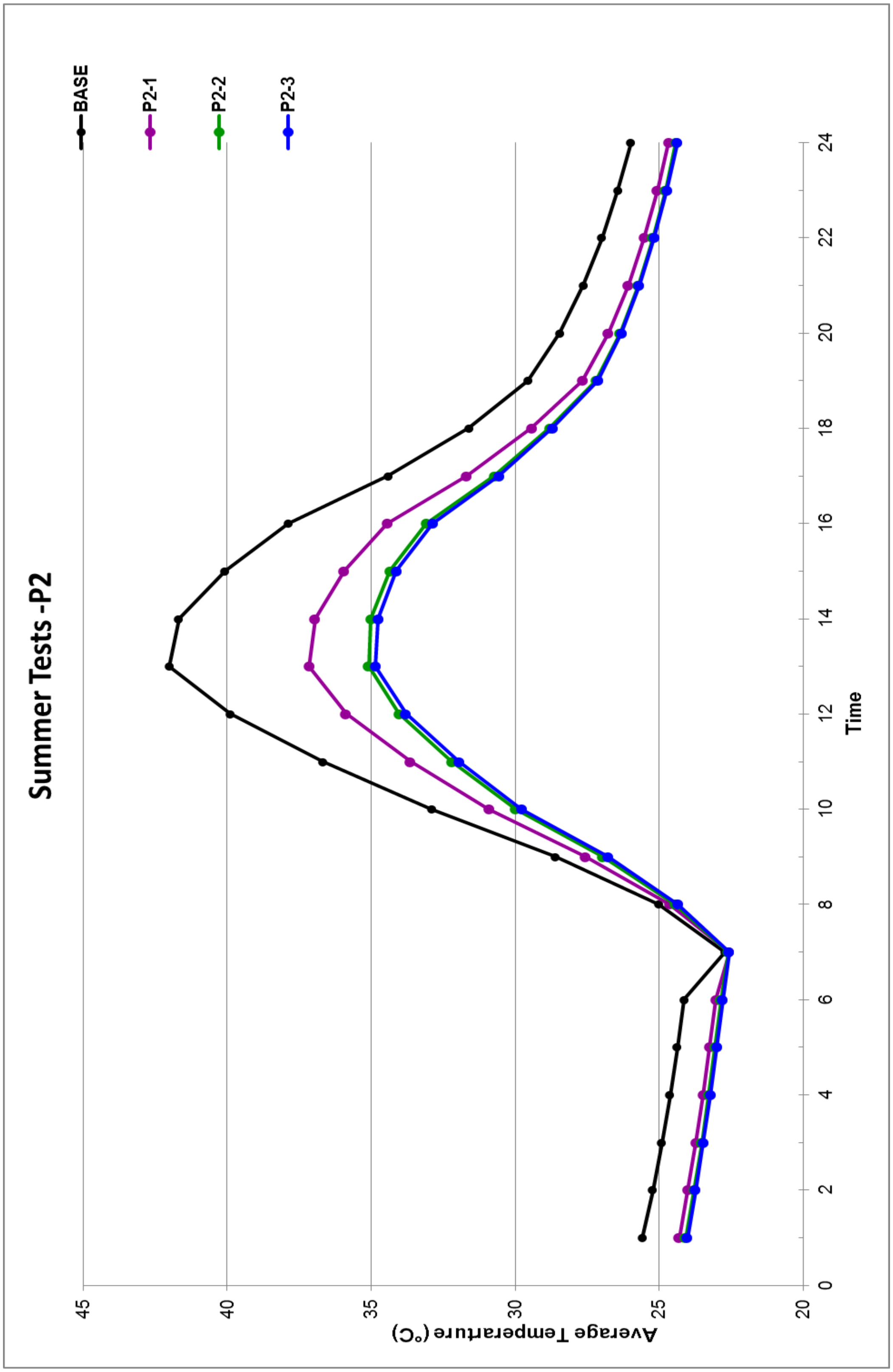


Figure B. 2: Average Temperature for Summer Test-P2

Table B. 3: Summary of Average Temperature (˚C) for Summer Tests-P3

Time	BASE	P3-1	P3-2	P3-3
1	25.57	23.78	23.20	24.07
2	25.22	23.47	22.99	23.78
3	24.90	23.18	22.81	23.52
4	24.62	22.93	22.65	23.28
5	24.36	22.69	22.50	23.06
6	24.12	22.48	22.37	22.85
7	22.71	22.40	22.88	22.60
8	25.01	23.78	24.38	24.44
9	28.60	25.83	26.21	26.96
10	32.89	28.36	28.26	29.97
11	36.68	30.43	29.82	32.20
12	39.90	32.22	31.32	34.02
13	42.01	33.37	32.17	35.09
14	41.68	33.45	31.82	35.01
15	40.07	32.89	31.20	34.34
16	37.88	31.80	30.22	33.08
17	34.41	29.96	28.49	30.71
18	31.60	28.33	26.93	28.79
19	29.55	26.91	25.52	27.18
20	28.45	26.13	24.89	26.36
21	27.64	25.50	24.41	25.73
22	26.98	24.97	24.02	25.21
23	26.44	24.52	23.70	24.78
24	25.97	24.13	23.43	24.40

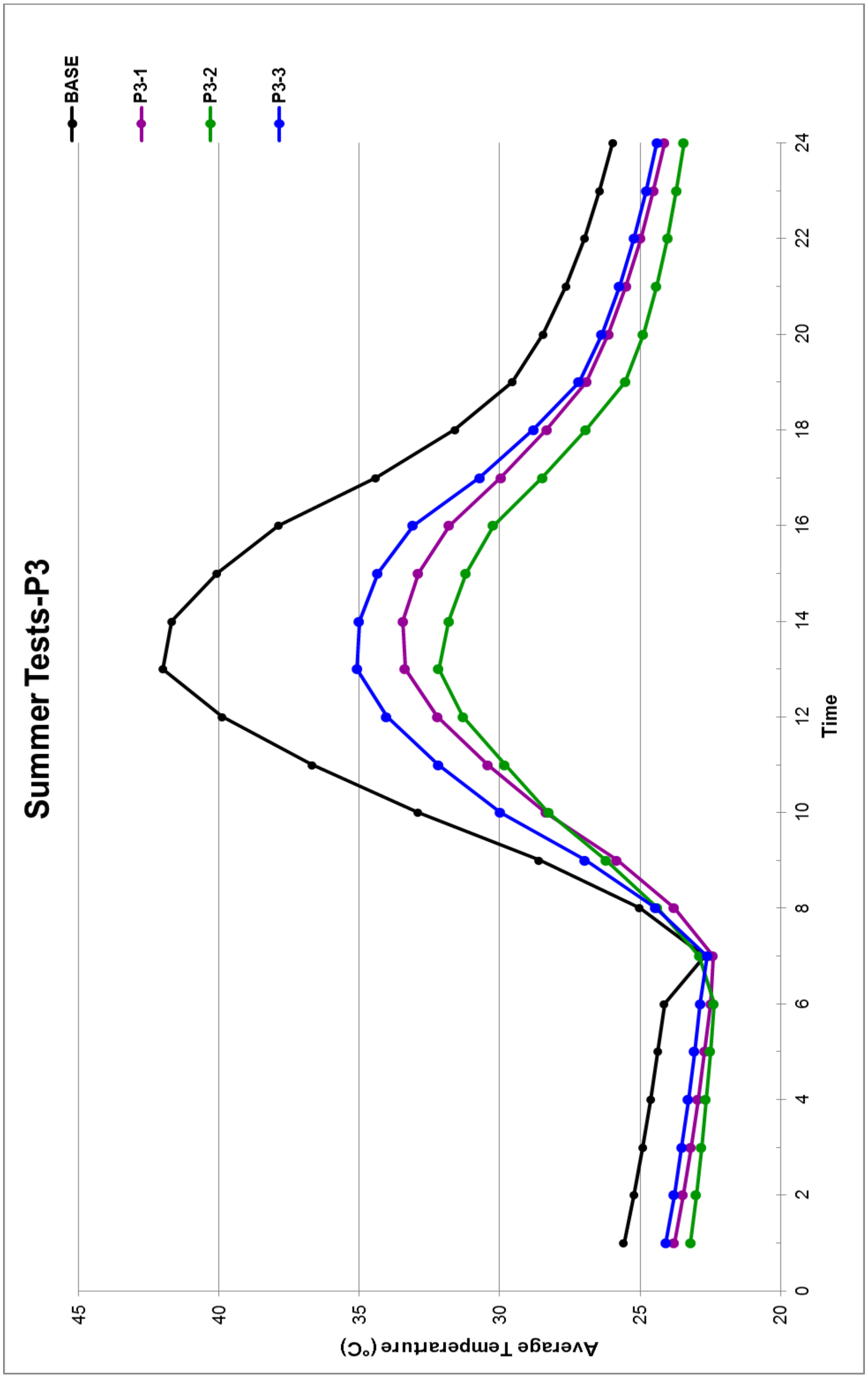


Figure B. 3: Average Temperature for Summer Test-P3

Table B. 4: Summary of Average Temperature (˚C) for Winter Tests-P1

Time	BASE	P1-1	P1-2	P1-3	P1-4	P1-5
1	14.76	14.12	14.05	14.18	14.18	14.21
2	14.53	13.93	13.85	13.98	13.97	14.01
3	14.33	13.75	13.66	13.80	13.78	13.83
4	14.14	13.58	13.48	13.64	13.60	13.67
5	15.36	14.82	14.76	14.90	14.85	14.89
6	15.36	14.82	14.76	14.90	14.85	14.89
7	16.58	16.06	16.03	16.16	16.10	16.12
8	16.16	15.77	15.69	15.85	15.76	15.80
9	17.16	16.73	16.56	16.72	16.68	16.66
10	18.82	17.83	17.57	17.42	17.78	17.35
11	20.65	18.86	18.51	18.17	18.75	18.10
12	22.30	19.69	19.21	18.79	19.39	18.72
13	23.38	20.08	19.52	19.15	19.69	19.09
14	22.85	19.78	19.44	19.12	19.63	19.08
15	21.82	19.41	19.15	18.90	19.37	18.87
16	19.28	18.79	18.62	18.48	18.84	18.46
17	18.73	17.75	17.81	17.74	18.00	17.74
18	17.74	16.54	16.69	16.63	16.87	16.66
19	17.04	15.98	16.06	16.05	16.23	16.08
20	16.47	15.54	15.57	15.60	15.73	15.63
21	16.01	15.18	15.17	15.23	15.32	15.26
22	15.63	14.86	14.84	14.91	14.97	14.95
23	15.30	14.59	14.54	14.64	14.67	14.67
24	15.02	14.41	14.28	14.39	14.41	14.43

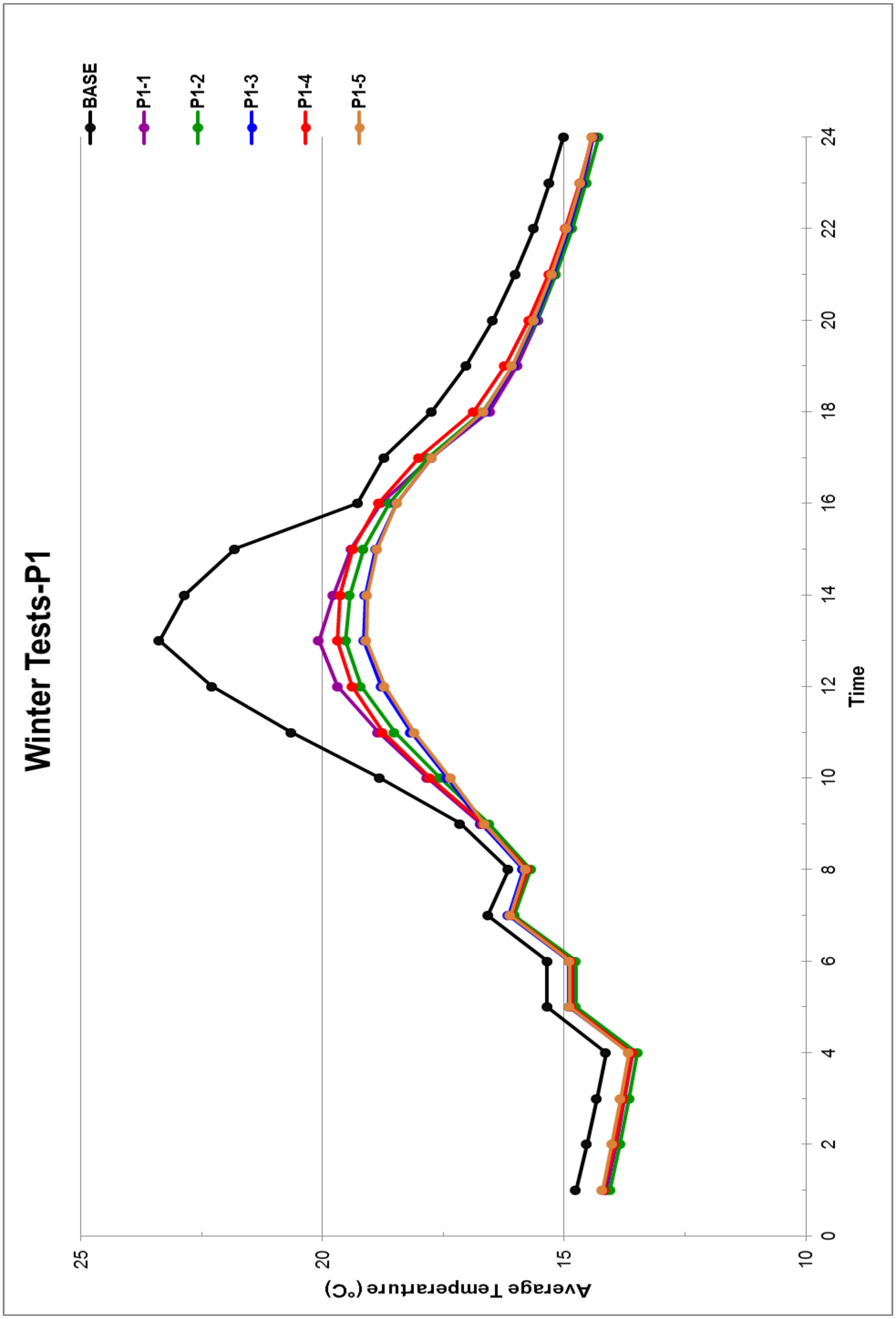


Figure B. 4: Average Temperature for Winter Test-P1

Table B. 5: Summary of Average Temperature (˚C) for Winter Tests-P2

Time	BASE	P2-1	P2-2	P2-3
1	14.76	14.19	14.18	14.16
2	14.53	13.99	13.98	13.96
3	14.33	13.80	13.80	13.78
4	14.14	13.63	13.64	13.62
5	15.36	14.90	14.90	14.87
6	15.36	14.90	14.90	14.87
7	16.58	16.16	16.16	16.13
8	16.16	15.84	15.85	15.83
9	17.16	16.75	16.72	16.69
10	18.82	17.64	17.42	17.36
11	20.65	18.59	18.17	18.07
12	22.30	19.24	18.79	18.68
13	23.38	19.57	19.15	19.03
14	22.85	19.48	19.12	19.02
15	21.82	19.19	18.90	18.82
16	19.28	18.69	18.48	18.43
17	18.73	17.89	17.74	17.70
18	17.74	16.74	16.63	16.60
19	17.04	16.13	16.05	16.02
20	16.47	15.66	15.60	15.58
21	16.01	15.27	15.23	15.21
22	15.63	14.94	14.91	14.89
23	15.30	14.66	14.64	14.62
24	15.02	14.41	14.39	14.38

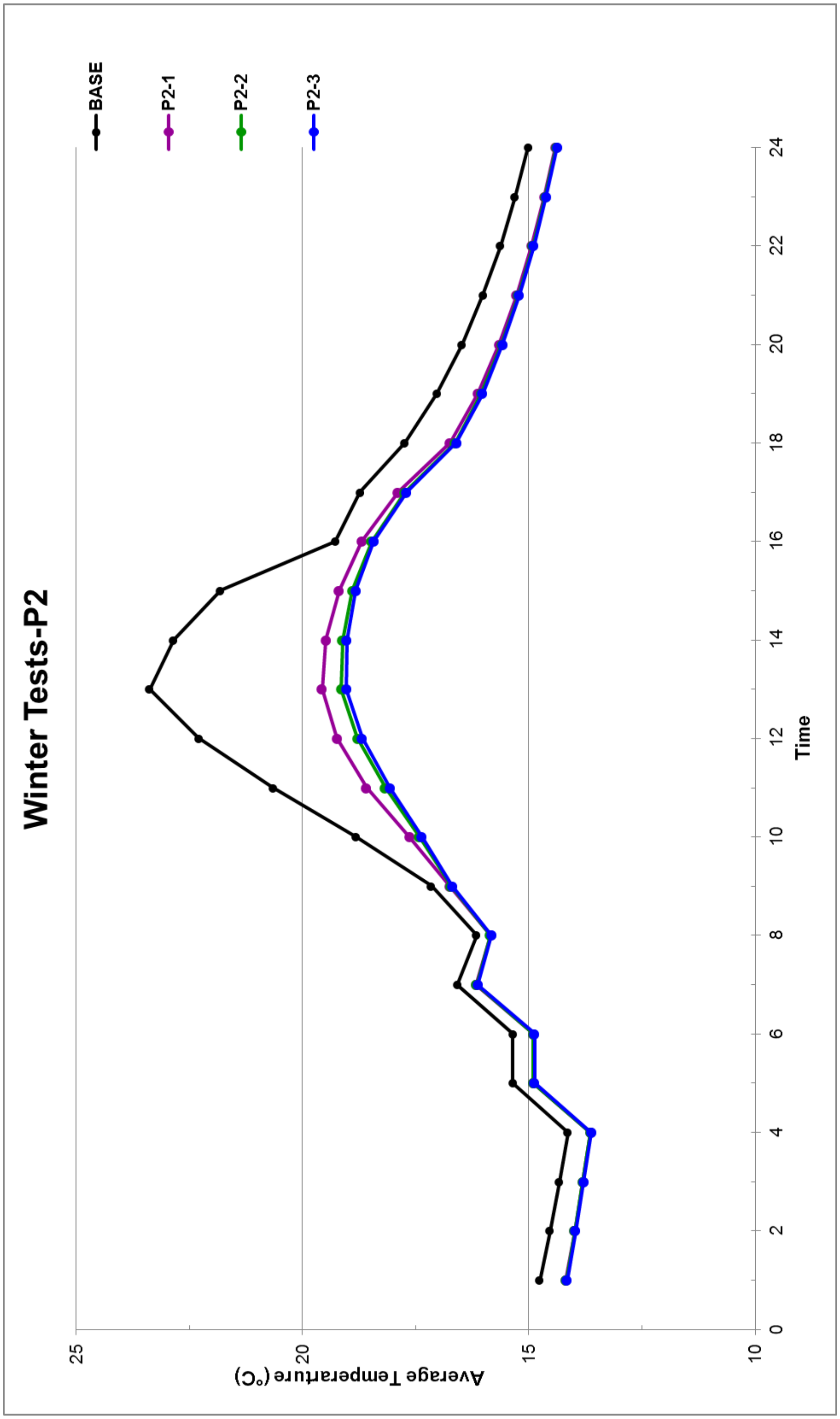


Figure B. 5: Average Temperature for Winter Test-P2

Table B. 6: Summary of Average Temperature (˚C) for Winter Tests-P3

Time	BASE	P3-1	P3-2	P3-3
1	14.76	12.51	13.71	14.18
2	14.53	12.32	13.56	13.98
3	14.33	12.13	13.42	13.80
4	14.14	11.97	13.29	13.64
5	15.36	13.06	14.41	14.90
6	15.36	13.06	14.41	14.90
7	16.58	14.15	15.52	16.16
8	16.16	13.88	15.33	15.85
9	17.16	14.64	16.36	16.72
10	18.82	15.30	17.30	17.42
11	20.65	16.03	17.91	18.17
12	22.30	16.63	18.32	18.79
13	23.38	16.97	18.56	19.15
14	22.85	17.05	18.62	19.12
15	21.82	16.86	18.44	18.90
16	19.28	16.48	17.97	18.48
17	18.73	15.83	17.03	17.74
18	17.74	14.87	15.81	16.63
19	17.04	14.34	15.28	16.05
20	16.47	13.92	14.89	15.60
21	16.01	13.56	14.57	15.23
22	15.63	13.25	14.30	14.91
23	15.30	12.97	14.08	14.64
24	15.02	12.73	13.88	14.39

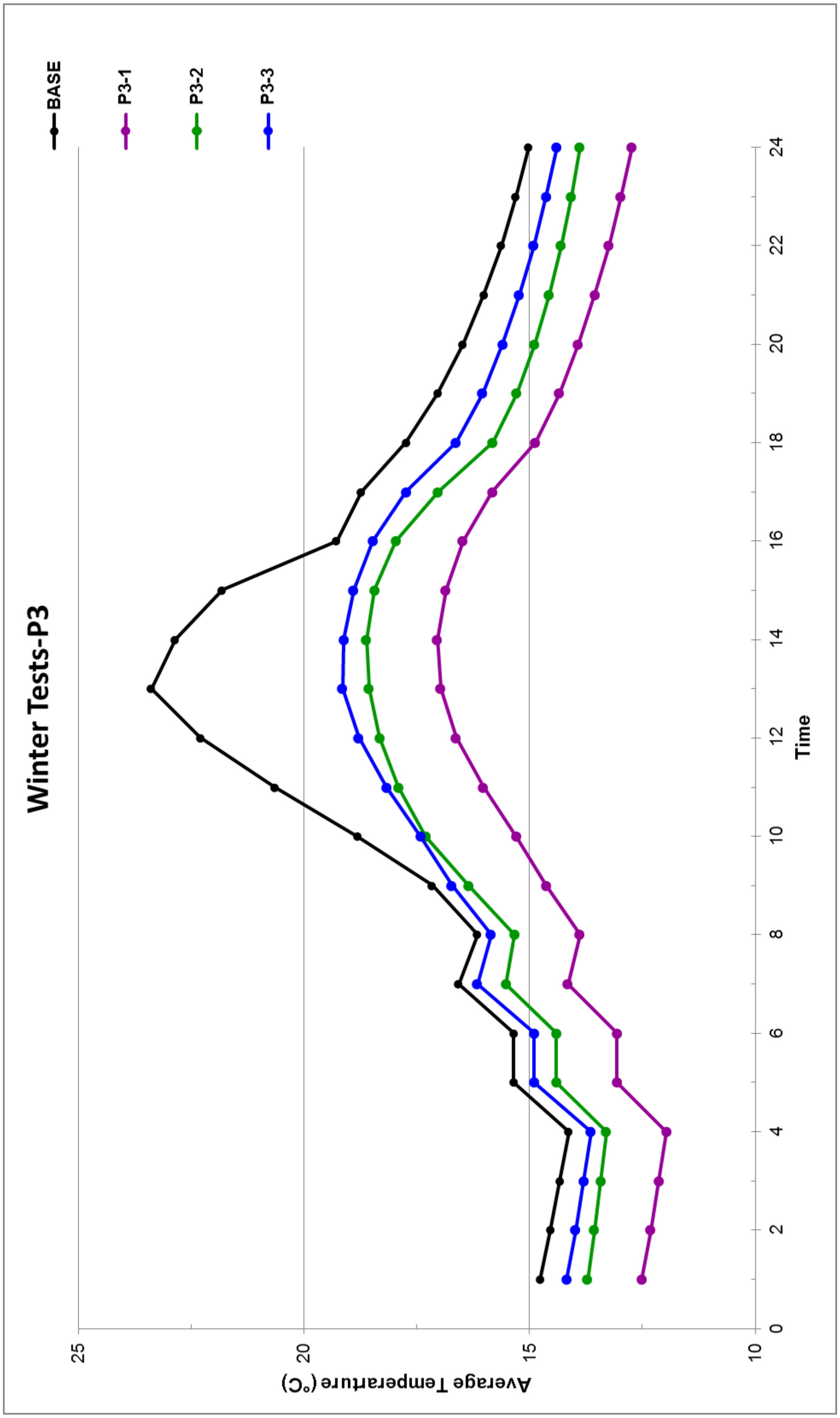


Figure B. 6: Average Temperature for Winter Test-P3

Appendix C Tabulated simulation results for all tests performed in Part Two of the research showing Average Surface Temperatures of urban areas excluding buildings.

Table C. 1: Summary of Average Temperature (˚C) for Summer Tests in Area A

Time	Existing Condition	Trees Plus Green Roof	Trees Only
1	35.27	33.81	33.98
2	35.04	33.62	33.78
3	34.84	33.46	33.61
4	34.67	33.32	33.46
5	34.51	33.20	33.32
6	34.16	33.09	33.19
7	24.63	24.33	24.38
8	27.87	27.24	27.32
9	32.20	30.01	30.33
10	37.04	32.89	33.40
11	42.28	36.22	36.77
12	47.58	40.42	40.84
13	50.98	43.69	44.15
14	50.27	42.69	43.44
15	47.10	40.95	41.75
16	44.23	39.91	40.43
17	42.05	39.04	39.43
18	40.22	37.96	38.27
19	38.33	36.31	36.58
20	37.37	35.51	35.75
21	36.72	34.98	35.21
22	36.23	34.59	34.80
23	35.85	34.27	34.48
24	35.53	34.02	34.21

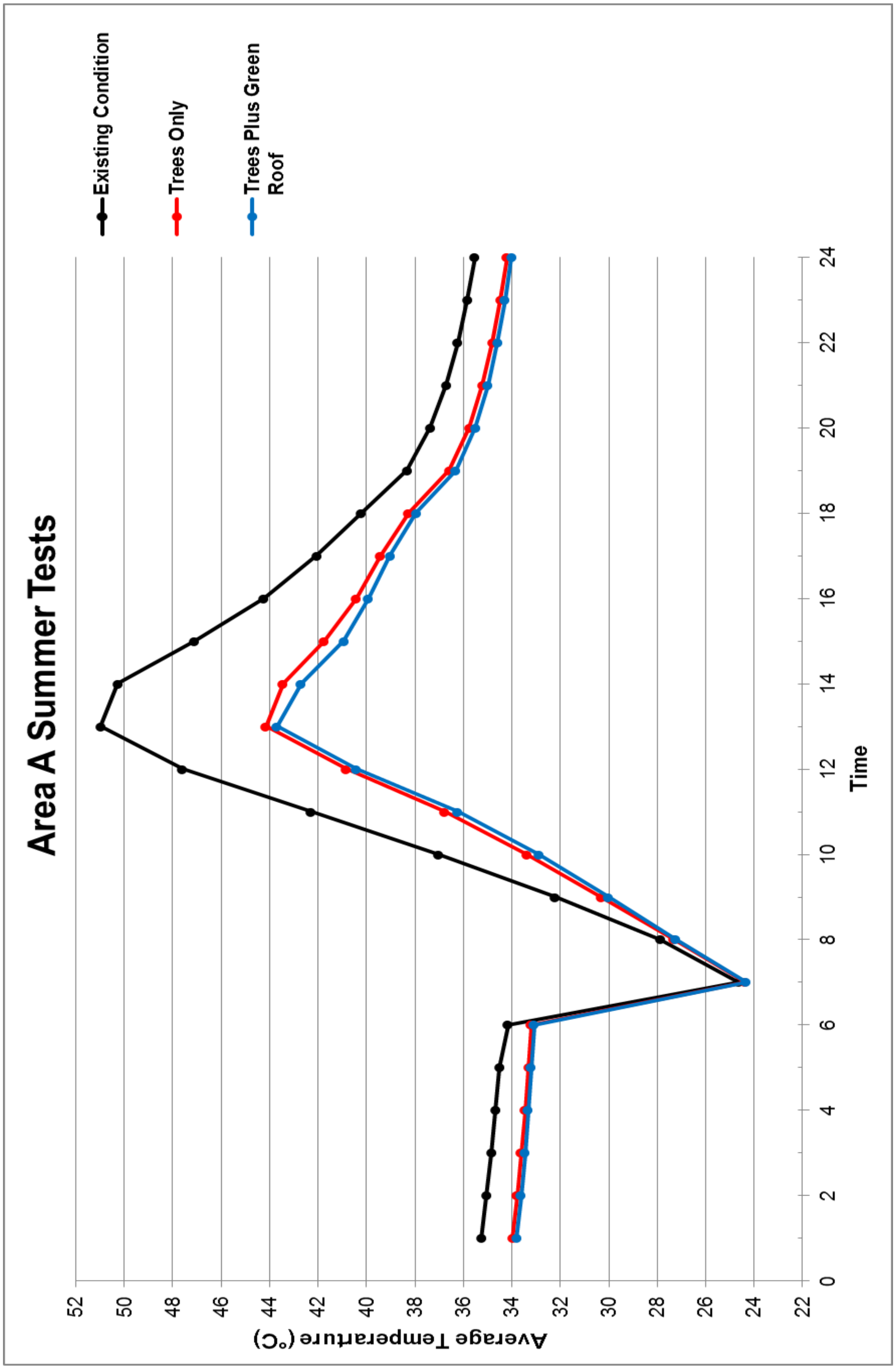


Figure C. 1: Average Temperature for Summer Tests in Area A

Table C. 2: Summary of Average Temperature (˚C) for Winter Tests in Area A

Time	Existing Condition	Trees Only	Trees Plus Green Roof
1	17.53	17.50	17.39
2	17.34	17.33	17.22
3	17.17	17.18	17.08
4	17.02	17.05	16.94
5	16.88	16.92	16.82
6	16.75	16.81	16.70
7	18.06	18.20	18.16
8	18.09	18.25	18.20
9	19.42	19.51	19.45
10	21.59	20.83	20.76
11	24.61	22.48	22.31
12	27.16	24.44	24.18
13	26.41	23.70	23.46
14	25.57	23.40	23.13
15	24.52	23.05	22.80
16	23.36	22.47	22.26
17	22.02	21.47	21.29
18	20.45	20.03	19.88
19	19.65	19.32	19.19
20	19.09	18.83	18.71
21	18.65	18.46	18.34
22	18.30	18.15	18.03
23	18.00	17.90	17.78
24	17.75	17.68	17.57

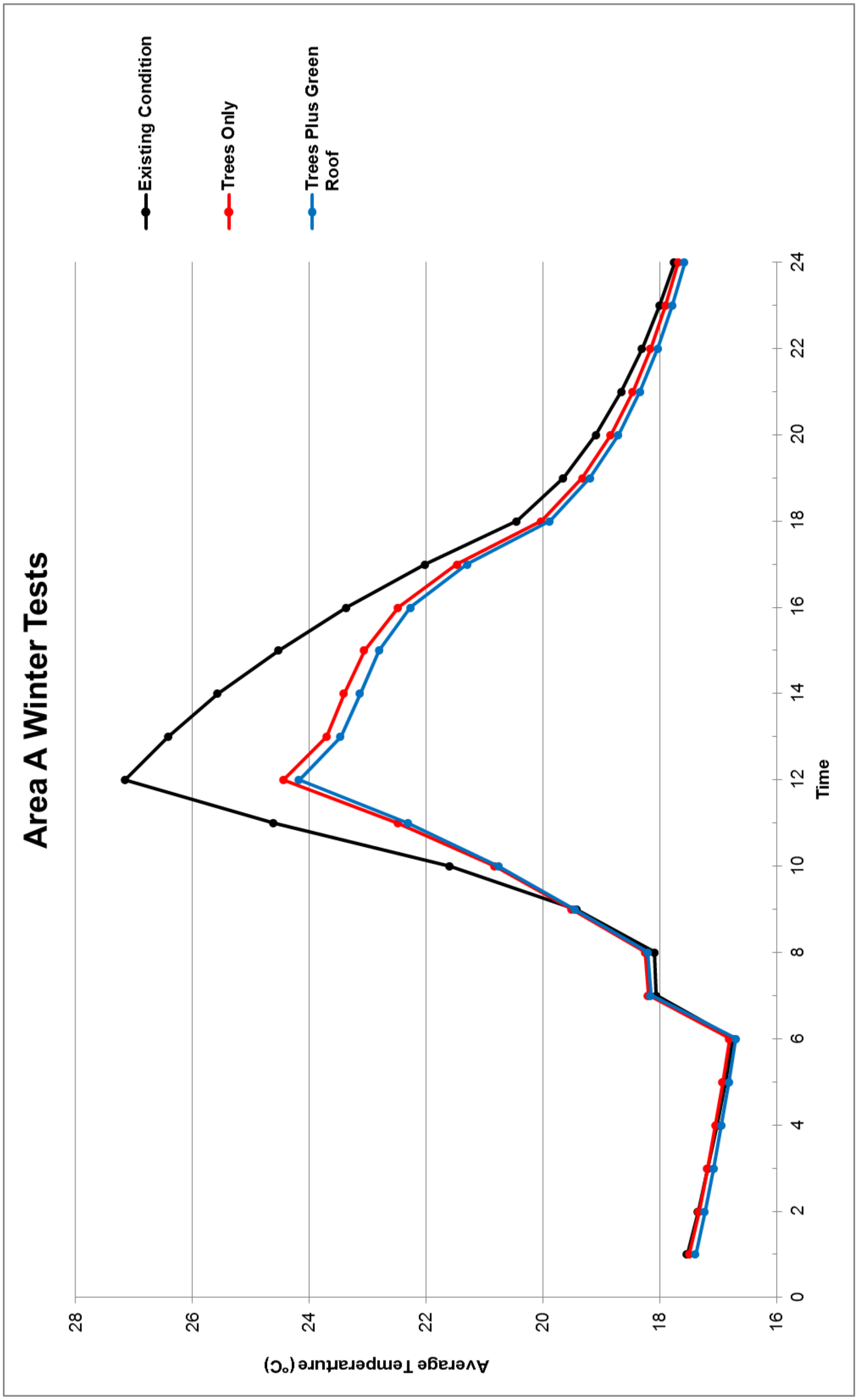


Figure C. 2: Average Temperature for Winter Tests in Area A

Table C. 3: Summary of Average Temperature (˚C) for Summer Tests in Area B

Time	Existing Condition	Trees Plus Green roof	Trees Only
1	30.09	27.37	27.23
2	29.88	27.26	27.10
3	29.69	27.15	26.99
4	29.52	27.07	26.89
5	29.38	26.99	26.80
6	29.25	26.93	26.73
7	23.10	21.60	21.95
8	26.34	22.82	23.97
9	29.74	25.67	25.75
10	33.22	27.59	27.65
11	36.53	29.41	29.48
12	40.06	31.75	31.87
13	43.32	33.98	34.23
14	43.20	34.24	34.47
15	41.55	33.68	33.84
16	39.59	32.62	32.77
17	37.08	31.68	31.76
18	34.93	30.58	30.60
19	33.08	29.18	29.17
20	32.14	28.57	28.52
21	31.50	28.18	28.11
22	31.02	27.90	27.80
23	30.65	27.69	27.57
24	31.13	27.57	27.51

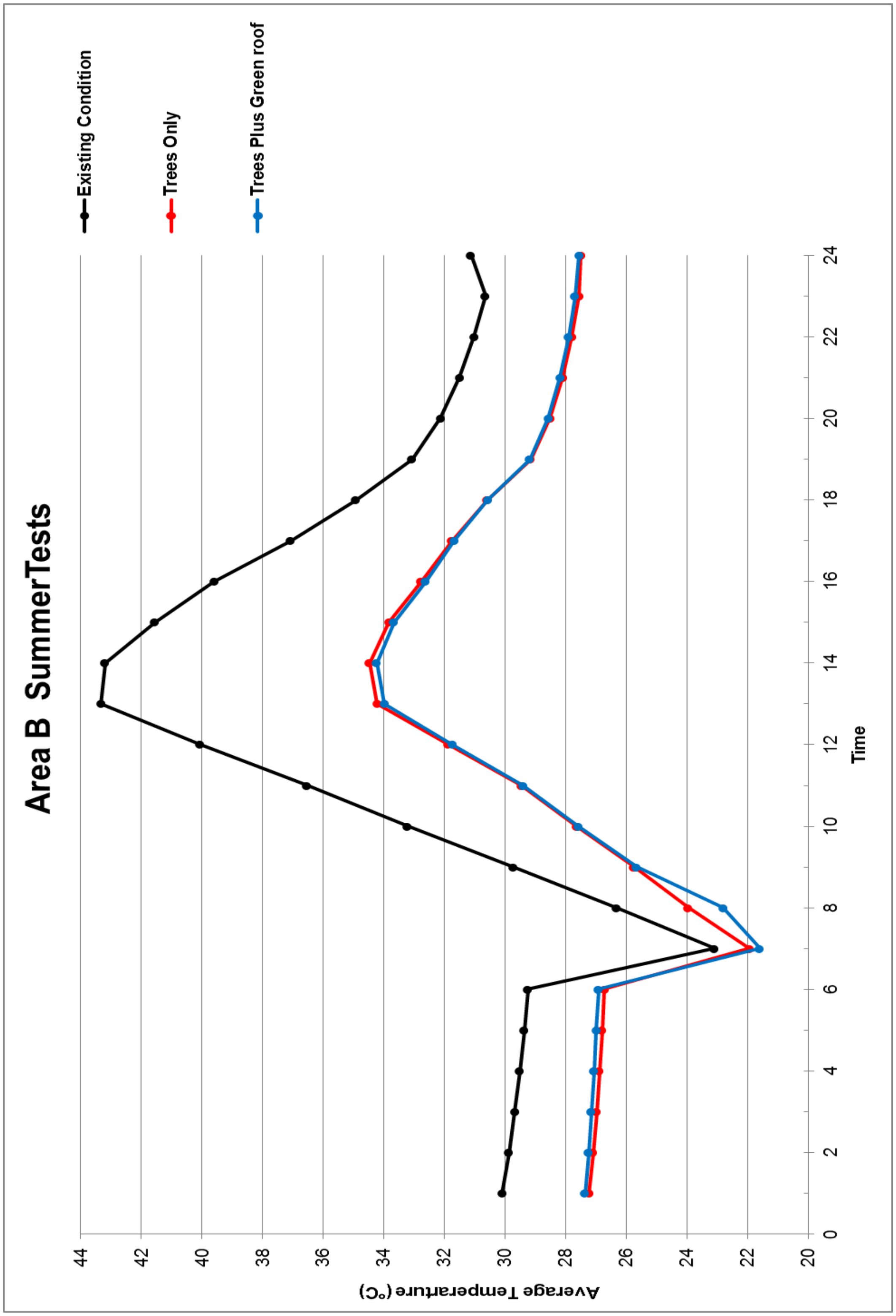


Figure C. 3: Average Temperature for Summer Tests in Area B

Table C. 4: Summary of Average Temperature (˚C) for Winter Tests in Area B

Time	Existing condition	Trees Only	Trees Plus Green Roof
1	15.99	14.50	14.40
2	15.83	14.39	14.29
3	15.68	14.29	14.20
4	15.54	14.20	14.11
5	15.42	14.12	14.03
6	15.31	14.04	13.96
7	16.66	15.41	15.37
8	16.57	15.31	15.26
9	17.44	15.99	15.93
10	18.71	16.70	16.60
11	20.42	17.49	17.30
12	22.49	18.68	18.37
13	22.96	18.81	18.50
14	22.72	18.68	18.42
15	22.31	18.50	18.27
16	21.37	18.05	17.85
17	19.98	17.25	17.08
18	18.56	16.19	16.04
19	17.85	15.72	15.58
20	17.36	15.39	15.26
21	16.97	15.14	15.02
22	16.66	14.93	14.82
23	16.40	14.77	14.66
24	16.18	14.62	14.52

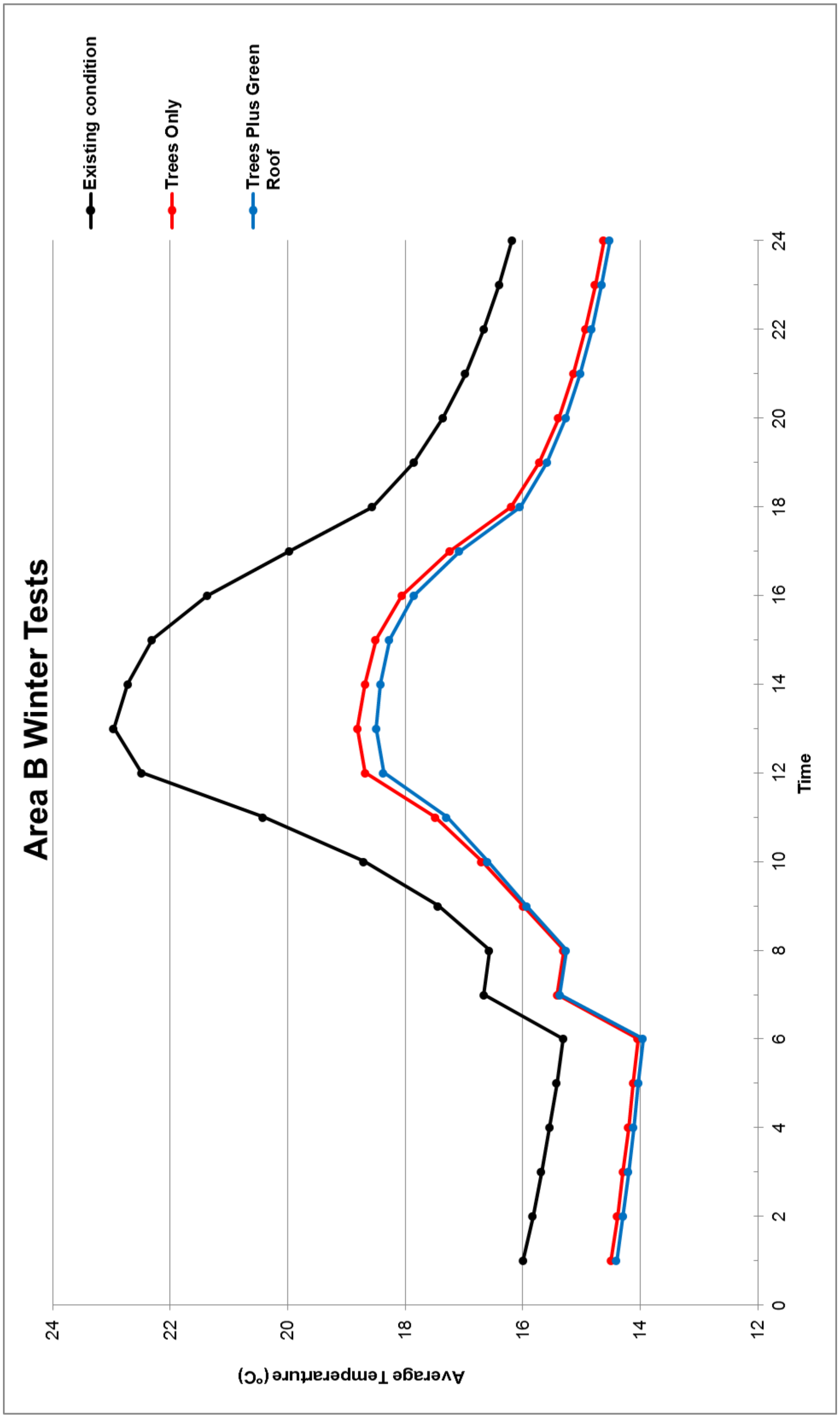


Figure C. 4: Average Temperature for Winter Tests in Area B