CLIMATE-SENSITIVE URBAN PUBLIC SPACE: A SUSTAINABLE APPROACH TO URBAN HEAT ISLAND MITIGATION IN COLOMBO, SRI LANKA

Narein Gerald Rajintha Perera

(03/9908)

Degree of Doctor of Philosophy

Department of Architecture

University of Moratuwa
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Declaration

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N G R Perera

The above candidate has carried out research for the Ph.D. thesis under my supervision.

……………………………………. ……………………………

Signature of Supervisor: Date:

Prof. P K S Mahanama

dedicated to;

my children; ananya, vinaya, dhruv

my wife; pendrine

and to my parents

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Abstract

Manipulating the urban fabric is fundamental to mitigate and adapt to the warming trend in the growing high-density tropical cities. However, excessive data needs, weak analytical methods and the un-coordinated planning regimes pose barriers to achieving this aim.

The main aim of the research is to bridge the gap in urban design-climate links, being translated into guidelines for real-world applicability in a background climate affected by global warming. The study is limited to the warm humid tropical climate of Colombo, Sri Lanka, as the experimental context for the research.

The main research questions are related to; the microclimatic background condition under current and future warming scenario; sensitivity of the key urban morphology variables that will define and drive the decision making process; and the planning and policy implications that link climate and urban design. The study employs the Local Climate Zone (LCZ) system as a method of contextual analysis, together with LCZ-based morphology simulations (ENVI-met), utilising Mean Radiant Temperature (MRT) as the key dependent variable. Statistical analyses (SPSS) of the results test the applicability and sensitivity of urban morphological variables to help mitigate / adapt to local and global warming.

The findings indicate that the Sky View Factor is the most influential urban indicator of local climate. In general, night-time shows better correlation with MRT. The nature of the Pervious Surface Cover has little or no effect on reducing MRT. And, the correlation of variables with MRT is stronger in a climatic background affected by global warming.

The work contributes a 'conceptual framework' for the deeper understanding of the effect of building morphology on local level warming in the tropics. Policies that give effect to these findings are presented in a manner that requires minimal data input. Protocols for mapping of LCZs and relative warming effects, and sensitivity analysis of key design parameters for the mitigation of UHI in the tropics are presented. The socio-economic and planning practice implications of a LCZ-based planning approach are explored.

Keywords: ENVI-met, Global warming, Local Climate Zones, MRT, Urban Heat Island, Warm Humid Tropics

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List of Abbreviations

AVA	Air Ventilation Assessment
BSF	Building Surface Fraction
CASBEE	Comprehensive Assessment System For Built Environment Efficiency
CMC	Colombo Municipal Council
CMRSP	Colombo Metropolitan Region Structure Plan
DGP	Development Guide Plans
FAR	Floor Area Ratio
GIS	Geographic Information System
GSF	Green Surface Fraction
HRE	Height of Roughness Elements
IPCC	Intergovernmental Panel on Climate Change
ISF	Impervious Surface Fraction
LCZ	Local Climatic Zones
LQ	Location Quotient
MRT	Mean Radiant Temperature
PET	Physiological Equivalent Temperature
PMV	Predicted Mean Vote
PSF	Pervious Surface Fraction
q	Specific Humidity
q.rel	Relative Humidity
RMSE	Root Mean Square Error
SHIM	Surface Heat Island Model
SPSS	Statistical Package for the Social Sciences
SVF	Sky View Factor
t	Temperature
UBL	Urban Boundary Layer
UCL	Urban Canopy Layer
UCMap	Urban Climate Map
UDA	Urban Development Authority
UHI	Urban Heat Island
u, v, w	Wind Velocity
wDir	Wind Direction
WMO	World Meteorological Organisation
wSpeed	Wind Speed
WUDAPT	World Urban Database And Access Portal Tools

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1.0 Introduction

1.1 Research Background - Urbanisation, climate change and the heat island effect

1.1.1 Climate and Climate Change

One of the major challenges facing urban planning and design is that of global climate change, primarily as a result of greenhouse gas emissions, and its regional consequences. This change is expected to occur within the planning life cycle (50 years) and will modify temperature and precipitation regimes, alter storm frequencies and magnitudes and cause sea-level rise. These changes will affect urban areas by changing the existing climate context within which they are placed and for which they may be adapted. (De Sherbinin et al., 2007) (as cited in Mills et al., 2010) Moreover, they will affect the resources of the surrounding landscape (water and food resources, for example) upon which the city relies for sustenance. (Mills et al., 2010)

Eriyagama et al. (2010) contended that;

> There is ample evidence to suggest that Sri Lanka's climate has already changed. During 1961-1990, the country's mean air temperature increased by 0.016 °C per year, and mean annual precipitation decreased by 144 mm (7%) compared to that of 1931-1960. It is suggested that Sri Lanka's mean temperature may increase by approximately 0.9-4°C over the baseline (1961-1990) by the year 2100) with accompanying changes in the quantity and spatial distribution of rainfall. Scientists attribute this warming trend seen throughout the country to both the enhanced greenhouse (global) effect as well as the 'local heat island effect' caused by rapid urbanization.

1.1.2 Public Space: Spaces between buildings

Public space is the stage upon which the drama of communal life unfolds. The streets, squares and parks of a city give form to the ebb and flow of human exchange. These dynamic spaces are an essential counterpart to the more settled places and routines of work and home life, providing the channels for movement, the nodes of communication, and the common grounds for play and relaxation. (Carr et al., 1992)

The specific reasons drawing people to public areas reflect many aspects of life, especially urban life. A stop in a public place may enable a person to rest and escape from the confusion, noise, crowds and "overload" (Milligram, 1970) in the surroundings - a common need in complex, urban settings. In this instance the place becomes a haven, a "stimulus shelter" (Wachs, 1979), providing contrast to the outside. It satisfies the periodic need people have to regroup their resources before moving on.

Comfort is a basic need. The need for food, drink shelter from the elements, or a place to rest when tired all require some degree of comfort to be satisfied. Without comfort it is difficult to perceive how other needs can be met. Shelter from whether the sun, the rain, or inclement weather, is an important but frequently neglected element of open space design. (Becker, 1973) (as cited in Carr et al., 1992) Comfort is also a function of the length of time people are to remain on a site.

It is clear that thermal comfort requirements are different for the outdoors from the indoors and that the outdoor experiences an altered microclimate in urban areas is also indisputable. The urban design question therefore is; how can these facts be translated into design actions that are often piecemeal and certainly carried out by different people acting at different places and times? (Emmanuel, 1993)

Urban designers in the equatorial tropics have to operate: high density, increasing urbanization and altered microclimate. Higher densities of urban growth are required of all tropical cities and that they should cool themselves by passive means in an ecologically sensible manner is clear.

Emmanuel (2005) states;

> Tay Kheng Soon (1993) argues that higher densities in the equatorial tropics are theoretically possible, provided common amenities are

adequately provided and access to common areas is used. Herein lays an important conceptual direction for climate conscious urban design in the equatorial tropics: the design of spaces between buildings in a climatically suitable way to ensure usability and accessibility.

1.1.3 The Heat Island Effect in the Tropics

The Urban Heat Island (UHI) phenomenon is best visualised as a dome of stagnant warm air over heavily built up areas of cities. UHIs have been observed in all parts of the world except in extreme cold climates. (Emmanuel, 2005) The Urban Heat Island is a function of urban built geometry, thermal properties, anthropogenic heat and pollution (Oke, 1982).

Studies of the urban climate of tropical cites suggest that the micro-climatic changes due to urbanization in the region are substantial and the anatomy of tropical heat islands bears a close resemblance to that of the temperate ones. (Oke, 1982) This has far-reaching implications for urban design in the tropics where night -time thermal stress is comparatively low. (Emmanuel, 2005)

There is evidence that the two phenomena – global warming and urban warming – feed off each other in major population centres, leading to an intensification of extreme heat events and human mortality (deaths caused by prolonged exposure) and morbidity (a marked in disease in the affected areas causing disability and/or overall poor health) (Tan et al., 2010). This in turn leads to more energy use, leading to a vicious cycle between local warming, energy use and emission. (McCarthy et al., 2010) The superimposition of urban warming on global and regional warming could be severe and calls for urgent mitigatory as well as adaptive action. (Parker, 2010)

Two disciplines, ‘architecture and urban design’ and ‘urban climatology’, dominate the published literature on how buildings and the urban environment affect climate (Mills, 1999). A key objective within architecture and urban design is the creation of a ‘comfortable’ living environment. Research on this topic often has a bioclimatic focus and an empirical and inferential approach and the results are normally presented as guidelines and real-world examples. In contrast, research in urban climatology, a special field within meteorology and climatology, focuses on measurements and the modelling of physical processes in order to interpret the changes in atmospheric properties that give rise to the “urban effect". With some exceptions, research within urban climatology is not carried out for the purposes of design and the results obtained are often theoretical and not readily interpretable from a design perspective. (Eliasson, 2000; Mills, 1999, 2006) (as cited in Eliasson et al., 2007)

Given the demographic and social importance of warm cities, Emmanuel (2011) queries as to;

- Could we direct urban growth in warm places to mitigate the heat island effect and simultaneously enhance their adaptive capacity to global warming?
- What urban design options work best to enhance the outdoor comfort in warm humid places?
- How do we promote higher density urban living in the warm humid belt without compromising human wellbeing?

1.2 Nature of the Research Problem

Urbanisation has consequences not only on local warming but also on regional and perhaps global warming. The rapid development of tropical megacities poses a special problem in terms of managing such local warming from reaching the regional/global scale. However, they also present an opportunity in that the increasing urban growth and associated infrastructure development could be used as a first line of defence against the vagaries of climate change. Such action remains within the urban planning and design domain and the phenomenon of UHI provides both a focal point as well as a political/policy opportunity to cities to contribute to the issue of adaptation to climate change. (Emmanuel, 2011)

In order to generate and realise such a planning approach, Mills (2006) outlines the following needs perspective;

1. The needs of designer (e.g. existing built forms and individual building needs),
2. A range of outdoor urban spaces,
3. The links between indoor and outdoor air,
4. Outdoor levels of comfort,
5. Case-studies that link design decisions to measurable impacts

Objective	Impacts	Limits		
		Buildings	Building groups	Settlement
Indoor comfort	Buildings	Location Materials Design (e.g. shape, orientation, etc.)	Access to sunlight and wind Air quality	Building codes
Outdoor comfort and health	Building Groups	Local climate change Emissions Materials/surfaces Building dimensions – flow interference & shadow areas	Building placement Outdoor landscaping, materials and surfaces Street dimensions & orientation	Guidelines on: Densities; Heights; Land uses; and Green-spaces
Energy use Air quality Protection from extremes	Settlement	Energy efficiency Air quality Urban climate effect	Mode and intensity of traffic flows Energy efficiency Air quality Urban climate effect	Zoning Overall extent and shape Transport Policy

Fig. 1 - Summary of tools to achieve climatic objectives, (Source - Mills, 2006)

In Fig.1 (Mills, 2006) presents a summary of the tools (grey diagonal) employed at the building, building group and settlement scales to achieve climatic objectives at those scales. The application of tools at each scale has a climate impact, shown below the diagonal cells, and places limits on decisions made at other scales, shown above the diagonal cells.

Good design at the scale of the building group is required if the broad objectives at the settlement scale are to be compatible with the specific needs of indoor spaces and the wider needs of outdoor spaces. The widespread incorporation of the tenets of sustainability into planning offers an opportunity for including climate/weather issues into urban design on a routine basis. The global concern for climate change and resource use provides a mandate for the development of a coherent and broad-based applied urban climatology, which has not existed previously. In particular, it encourages research that is guided by the needs of planners/designers. Thus far, studies on urban design-climate links have been limited in scope and much of the available research does not translate into clear guidelines that are supported by scientific knowledge and illustrative case studies. (Mills, 2004)

(Alcoforado, 2006) presents a framework of research design goals for achieving planning procedures toward high climatic quality cities. It is based on Mills' papers of 2003 and 2006, outlining his ideas on the meteorologically utopian city (Metutopia). (Fig. 2)

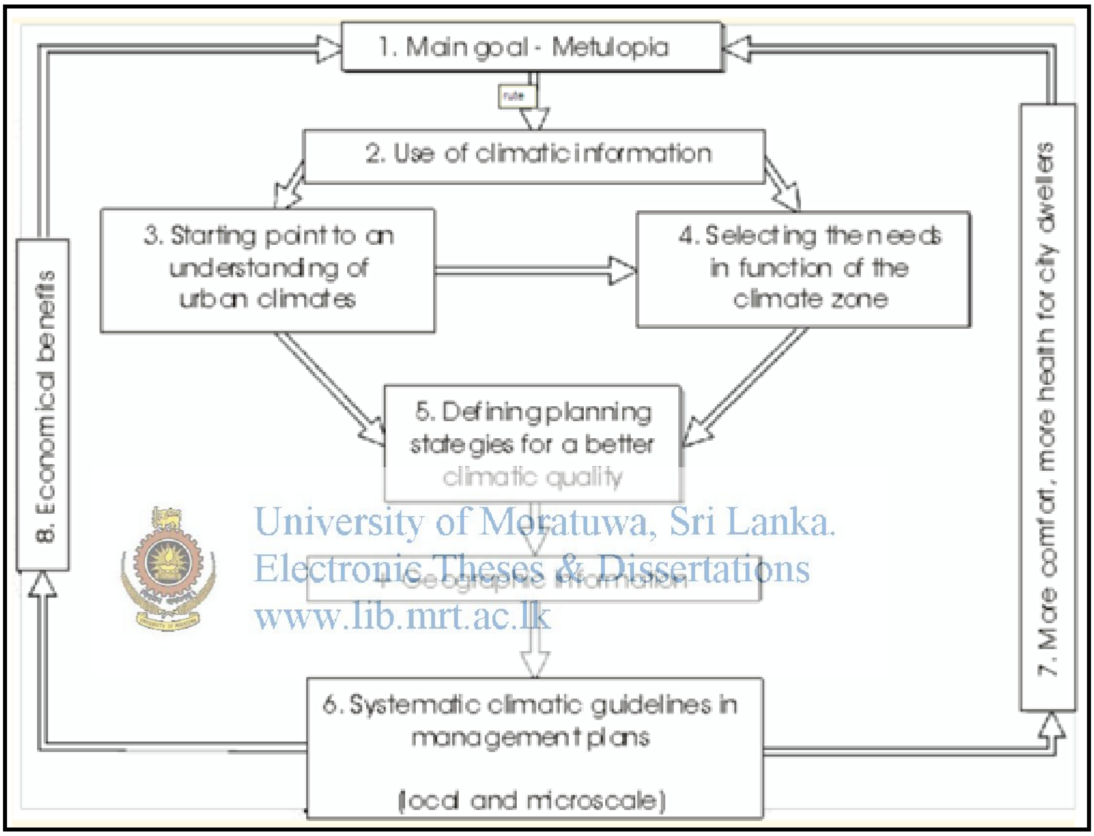


Fig. 2 - Flowchart showing different stages of research. (Source - Alcoforado, 2006)

Distinct steps are identified within this system;

- The use of climatic information
- Starting point to an understanding of urban climates
- Selection of the needs for different climate zones
- Defining planning strategies

These steps are taken as precedence developing the systematic process to achieve the research aims defined in the following section.

The Research Problem

The primary research problem identified is the lack of a strong morphological and climatic base for urban design, planning and policy to be established upon - in the warm humid tropical settings, both in the existing climate background as well as a future context warmed by the effects of global warming. The need for such a base to be formulated in data-scarce background - in rapid manner - to enable quick, yet, relevant decision making to take place, is deemed essential. The sensitivity of urban indicators ingrained in the system - which can be easily interpreted by designers - are identified as key design parameters essential for such an approach.

Primary research gaps are identified based on the above and the literature review in Chapter 2, Chapter 3 and detailed out in Chapter 2.7.

- Protocols for LCZ (Local Climate Zone) deployment in data- scarce tropics
- Sensitivity analysis of what are the key design parameters for the mitigation of UHI and Outdoor Thermal Comfort in the tropics
- Conversion of findings into planning strategies

These link back to the research questions highlighted below, in 1.3.

1.3 Aim, Research Questions and Limitations

Aim

The main aim of the research is in;

Bridging the gap in urban design-climate links, being translated into guidelines for real-world applicability in a background climate affected by **Global Warming.**

Limited to the **warm humid tropical** climate of **Colombo**, **Sri Lanka,** selected as an experimental context for the research.

Research Questions

In order to achieve the aim of the study, the following questions should be answered;

1. What is the microclimatic background condition that climate sensitive urban policy needs to be based upon?

The first step to improve urban climates is to study them using climatic information. Meteorological stations (either traditional or automatic), complying with WMO rules, provide useful data to understand climate at the macroclimatic scale. However, these data are not appropriate for urban studies, due to the spatial scale of study and to the particular atmospheric processes that occur in the urban atmosphere. (Alcoforado, 2006)

With a main objective in generating planning and policy decisions on urban design, a focus on the microclimate and local level warming is deemed applicable. Therefore;

a. What is the existing and therefore the predominant urban fabric morphology of the city?

b. What is the comparative the microclimatic effects of such a morphology in terms of 'Local Warming'?

2. What are the key urban morphology variables (Geometric and Surface Cover) that will define and drive the decision making process, at both the existing as well as a warmed urban microclimate?

The main requirement is to adapt to or mitigate the negative effects of a warmed microclimate in the microscale. The objective is to link the variables used in urban design to climate sensitive design.

a. Which of the variables are most sensitive to effecting Mean Radiant Temperature (MRT) (taken as the dependent variable throughout the research), considering a varied combination of patterns encompassing;

i. location within the urban context

ii. urban fabric morphology

iii. time of day

iv. orientation of the public spaces / streets

3. What are the planning and policy implications that can be generated to adapt to or roll-back the negative effects of a warmed urban microclimate?

The next step is to use climatic knowledge when designing and planning at different spatial scales by choosing planning strategies for a better climatic quality. (Alcoforado, 2006)

<u>Limitations of the research</u>

The study is limited to the warm humid city of Colombo, Sri Lanka.

The focus is on climate sensitive urban public space, therefore the research is limited to the urban canopy layer. It analyses the causes and effects of changing morphology at a 1.5m height above the ground, termed street level. The height that a person on the street would perceive the environment.

Local climate mapping to ascertain the critical ' Local climate zones' are simulated for conditions of calm and clear skies.

The global warming background scenario assumes microclimate that has seen a temperature change only.

The study was carried out for a particular day in April (simulation date 15.04.2013), since this month is deemed the most critical time of the year and therefore the worst -case scenario to be designed for.

1.4 Structure of the Thesis

This thesis consists of five chapters.

Chapter 1 deals with background and the nature of the research problem. It concludes with the definition of the main aims and questions of the research.

Chapter 2 is a review of literature encompassing the central topics of the thesis. A focus climate variability and change, its effects on the microclimate of the Urban Canopy Layer and urban warming in warm humid regions in general and Colombo, Sri Lanka in particular. The chapter discusses literature that deal with strategies to ameliorate urban warming, especially in warm, humid cities. Finally it summarises the studies with an identification of research gaps that forms the basis for the main research aims highlighted in Chapter 1.

Chapter 3 presents the research methods which have been used in the study. It is approached in three parts that use the preceding part to generate the required data for simulation and analysis in the next. The parts also discuss literature relevant to each process adopted as a detailed discussion to what was presented in Chapter 2.

Chapter 4 includes the results and discussion of the simulation study. An analysis protocol using statistical analysis forms the core of the discussion. The chapter is concluded with a ‘Summary of Findings’ and its links / variances to existing knowledge and results of the LCZ classification presented as a part of Chapter 3. These findings establish the basis for Chapter 5.

Chapter 5 contains implications for policy and planning for the design of climate-sensitive public spaces, in a warm, humid climate. Particular emphasis is placed on Colombo, Sri Lanka as the experimental context for its application.

Chapter 6 concludes the thesis with a summary of findings and contributions. It also includes identification of limitations, methodological challenges and potential areas for future research.

2. Literature review

This chapter contains a literature review of the critical concepts of this thesis. Literature specific to particular aspects covered in this thesis, especially relating to the Research Design are covered at those specific points of discussion.

2.1 Sensitivity of cities to climate variability and change

Cities and their inhabitants are key drivers of global climatic change. The large and ever increasing fraction of the world's population that lives in cities uses a disproportionate share of resources and produces climate-altering atmospheric pollutants. (Grimmond et al., 2010)

Fig. 3 - Interactions between urban areas and global environmental change. A conceptual framework. (Source - ugec.org)

Mills (2007) demonstrates that the anthropogenic emissions of carbon dioxide are highly concentrated in and near urban centres. Fig. 4 illustrates global emissions of carbon dioxide due to fossil fuel use calculated for 1 × 1° latitude–longitude grid (Andres et al., 1997). The geography of emissions corresponds closely to the locations of wealthy cities. For example, note the distribution of carbon injections into the atmosphere in Western Europe, the tall spikes in Japan and the lower peaks in eastern China. By contrast, much of Africa and India is characterized by the absence of these carbon peaks, despite the enormity of some cities (e.g. New Delhi and Lagos) located in these regions. The global economic disparity is revealed here as a disparity in urban-sourced emissions. (Mills, 2007)

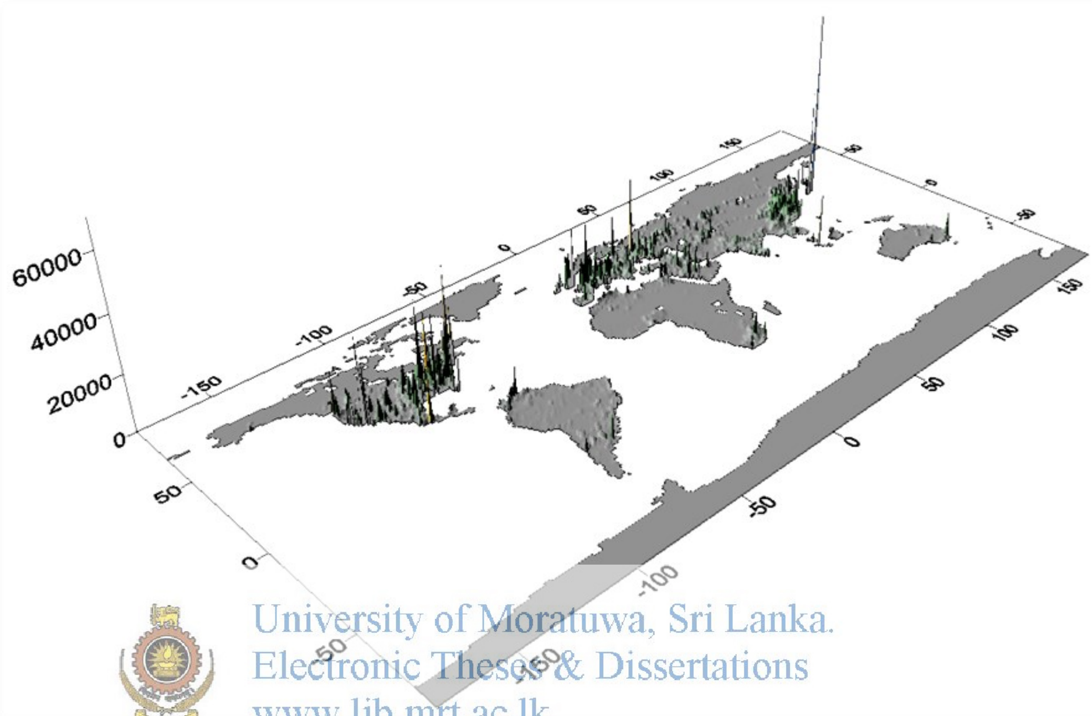


Fig. 4 - Estimated carbon dioxide emissions in 1995 in 000's of metric tons (t) of carbon per 1° × 1° latitude/longitude grid cell. These values are the summed emissions from fossil-fuel burning, hydraulic cement production and gas flaring. The highest value recorded is approximately 70 000 Mt. (Source - Andres et al., 1997 as cited in Mills, 2007)

Consumption and production of resources for use within urban environments have local and remote implications for ecosystem services, hydroclimate, energy provision, health, and other factors of human wellbeing (Grimm et al, 2008; Foley et al., 2005). At the same time, how cities choose to expand and develop will be critical to defining how successful society will be in adapting to global change. Because cities are, in a real sense, fundamental units of both climate change adaptation and mitigation, development choices in the coming century will lead to either significant exacerbation or significant reduction in the impacts of global change. (Bierwagen et al., 2010). (as cited in Georgescu et al., 2014)

A synthesis of studies strongly demonstrate that the spatial agreement between regions of significant warming across the globe and the locations of significant observed changes in many natural systems consistent with warming is very unlikely to be due solely to natural variability of temperatures or natural variability of the systems.

Several modelling studies have linked some specific responses in physical and biological systems to anthropogenic warming, but only a few such studies have been performed. Taken together with evidence of significant anthropogenic warming over the past 50 years averaged over each continent (except Antarctica), it is likely that anthropogenic warming over the last three decades has had a discernible influence on many natural systems. {WGI 3.2, 9.4, SPM; WGII 1.4, SPM} (IPCC, 2007) Mills (2007) cites a summary table by (McCarthy et al., 2001) summarising Human settlements impacts, categorised by state of scientific knowledge in Table 1.

Table 1 - Human settlements impacts, categorised by state of scientific knowledge.
Source - (McCarthy et al. (2001) as cited in Mills, 2007)

LOW Level of Agreement HIGH		
	Established but incomplete	**Well established**
HIGH	Increased vulnerability of infrastructure to urban flooding and landslides Tropical cyclones more destructive Fire danger to urban wildland-fringe infrastructure increased Sea-level rise increases cost/vulnerability of resource based industry Water supplies more vulnerable	Sea-level increases cost/vulnerability of coastal infrastructure Energy demand sensitive; parts of energy supply vulnerable Local capacity critical to successful adaptation Infrastructure in permafrost regions vulnerable
	Speculative	**Competing explanations**
LOW	Fire damage to key resources increased More hail and windstorm damage	Heat waves more serious for human health, resources Non-climate effects more important than climate Heat island effects increase summer energy demand Increased air and water quality problems
	LOW — Amount of Evidence	HIGH

Some of the early efforts to link the global warming trends to land use and land cover changes induced by urbanisation were made in 1980s and 1990s (Kukla, 1986; Changnon, 1992; Gallo, 1993; Gallo et al., 1996). The significance of urban warming to human health was revealed as early as the 1970s (Buechley, 1972; Clarke, 1972). Given the land area occupied by cities (less than 3% of global land area, UNFPA, 2007), it is unlikely that urban climate changes have a large direct effect on global climate change (Voogt, 2004; Parker, 2010). However, the intense energy and material use as well as pollution in cities that directly lead to urban warming has global consequences. (as cited in Emmanuel et al, 2011)

2.2 Microclimate of the urban canopy layer

Scales and surface description

Grimmond et al., (2010) contend that:

> An appreciation of spatial scale is key to understanding urban climates, observations and modelling. At global and regional scales, a city's climate, and its effects on climate, are influenced by its geographical setting: latitude, continentality, openness to synoptic events, proximity to water, surrounding topography, etc. These factors also influence the design of a city (for example, building styles) and the behaviours and activities of its inhabitants (demands for heating, cooling, etc.). Cities themselves are a source of buoyant, warm, polluted air that can modify precipitation patterns, especially downwind (Lowry, 1998) (Shepherd, 2005) and air quality and atmospheric chemistry thousands of kilometres away from the source. Within a city, neighbourhoods with similar land use and land cover, generate distinct local-scale climates (10^2–10^4 m). These are a function of the urban morphology, built materials, amounts of vegetation, and human activity (amounts of heat, water, etc., released). A simple urban-based climate classification system can distinguish areas by aerodynamic roughness, mean aspect ratio and impermeable surface cover (WMO, 2006) (WMO, 2008). At smaller spatial scales (10^0– 10^1 m), a person in a city experiences a range of conditions: sunlit or shaded areas of street; channelling or no wind; influence of a park or shade trees.
>
> At this scale, key features that need to be included in surface description are: (a) surface roughness length, because it influences wind flow; (b) impervious surface fraction, as it is key to energy partitioning between heat and moisture exchanges; (c) sky view factor as it influences solar access and radiative cooling; (d) thermal admittance as it modulates heating and cooling cycles of materials; (e) albedo as it influences surface heat absorption and (f) anthropogenic heat flux as it is an additional source of energy for the system (Stewart & Oke, 2009).

Structure of urban atmosphere

Unger et al., (2011) citing Oke, (1976) contends that:

> Two layers can be distinguished in the urban atmosphere. The first one is the urban canopy layer (UCL) containing air between the urban roughness elements (mainly buildings). It is a microscale concept, and its climate is dominated geographical factors and modified by the nature of the immediate surroundings. The upper boundary of the UCL is at about roof level. The second layer is the urban boundary layer (UBL) which is situated directly above the first layer. This is a local or mesoscale concept whose characteristics are governed by the nature of the whole urban area. (Fig. 5)

The Urban Boundary Layer (UBL)

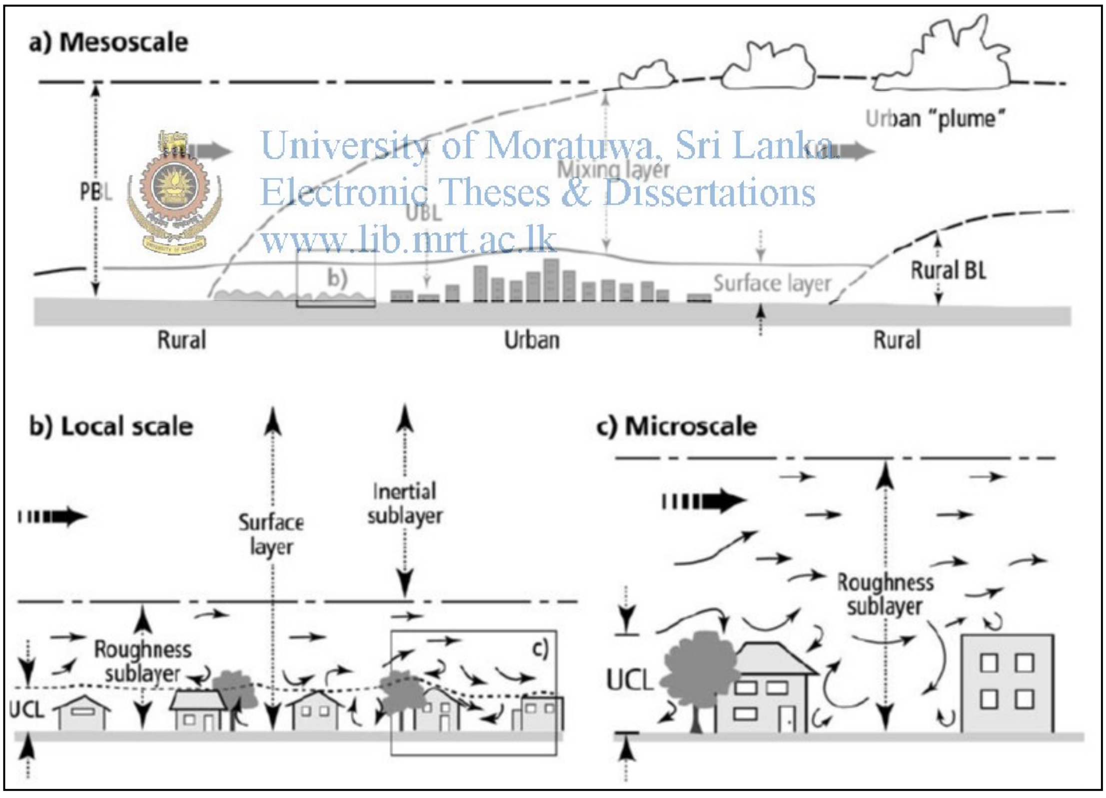


Fig. 5 - Structure of the urban atmosphere. Source - (Oke 1997, 2006)

This is the layer of air above the city whose properties are linked to the underlying urban surface. The UBL grows in height from the upwind edge of the city and extends beyond the urban area as an elevated plume. (Fig. 5 and Fig. 6)
There are several sub-layers within the UBL;

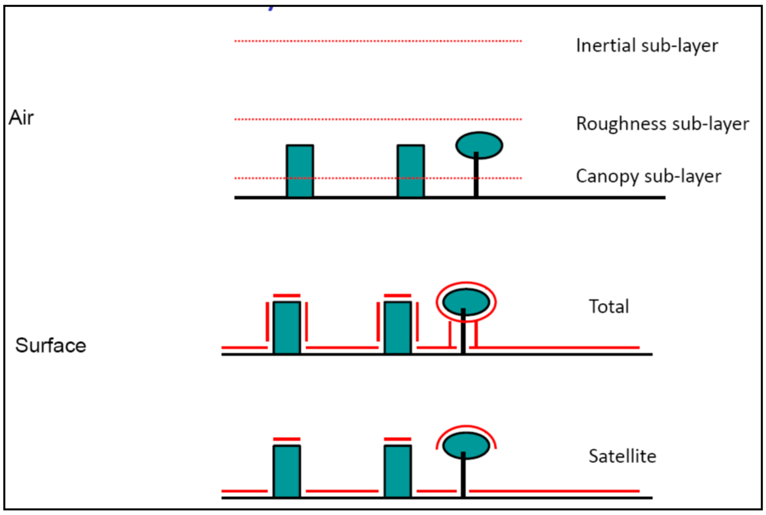


Fig. 6 - The urban boundary layer - what the sensors see.
Source - (Mills, 2011)

- **The Inertial Sub-layer (ISL)**: The lower part of the UBL extending from about 2-2½ times the height of buildings to 1/10 the height of the UBL. Here the fluxes of sensible and latent heat are nearly constant with height and the effects of individual surface types are 'blended'. Measurements here are representative of the underlying urban terrain (e.g. suburban).

- **The Roughness Sub-layer (RSL)**: This comprises the lowest layer of the atmosphere and is highly turbulent. Observations here will measure contributions from a great variety of distinct urban surfaces (roofs, gardens, etc.) which may be difficult to attribute.

The Urban Canopy Layer (UCL)

This is the layer of air at and below the average height of buildings and tree canopies. It lies within the Roughness Sub-layer.

The UCL is conceived as consisting of two parts;

- **The outdoors**: This is the open spaces between buildings. These spaces are exposed to the natural elements and are usually weakly managed. The positions of the urban components (buildings, trees, walls, etc.) regulate access to the sky and the movement of air. This is the source of much of the urban emissions, particularly from traffic.
- **The indoors**: This is the enclosed space within buildings, which are strongly managed for a purpose –often the comfort of inhabitants. The indoor climate is controlled through combinations of building design, inhabitant behaviour and heating/cooling systems.

(Mills, 2011)

"In the course of urban climate development, the near-surface air or (UCL) temperature shows the most obvious modification compared to the rural area (Oke, 1987). This urban warming is commonly referred to as the urban heat island (UHI), and it is a good example of inadvertent climatic change." (Unger et al, 2011)

2.3 Evidence for urban warming in warm, humid regions

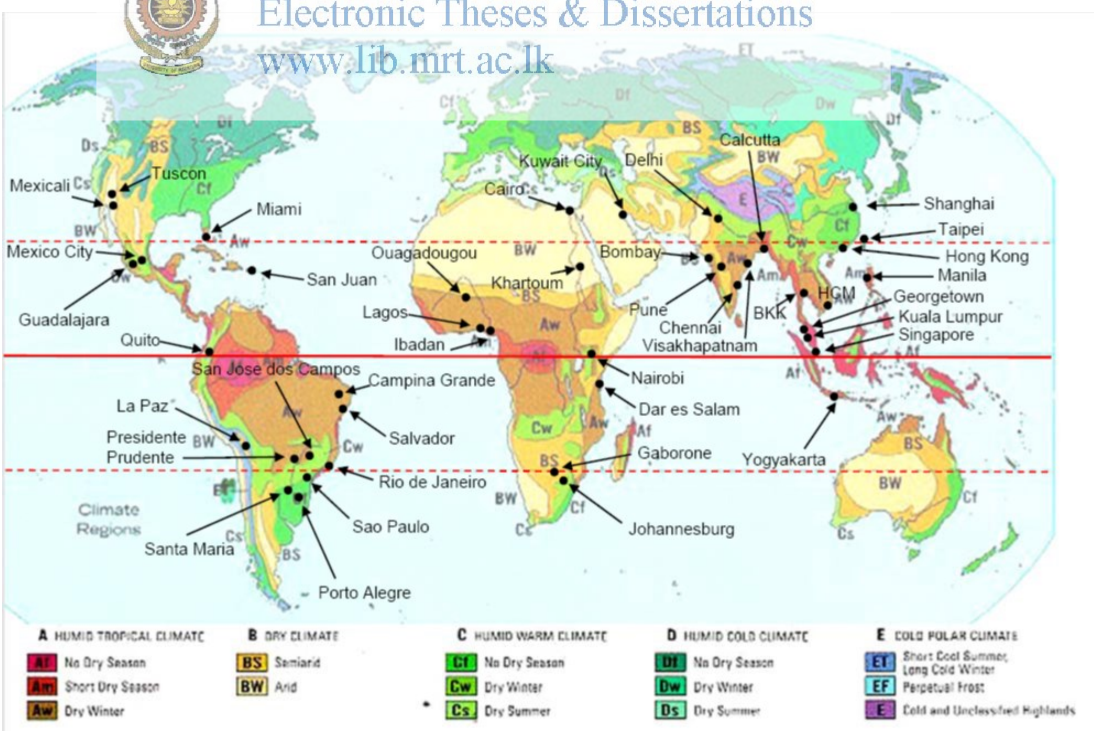


Fig. 7 - Geographic distribution of climates, highlighting work in (sub) tropical regions.
Source - (Roth, 2011)

Roth (2007) states:

> Over the last 50 years the developing world, much of which is located in (sub) tropical regions, has seen a dramatic growth of its urban population associated with serious degradation of environmental quality. (Roth, 2007) The total number of (sub) tropical urban climate studies, however; is still small (*<20% of all urban climate studies).* The available work is further biased towards descriptive studies rather than process work that seek to indicate the physical climatology of (sub) tropical cities. (Fig. 7).

An extensive survey of UHI studies evaluated by Stewart (2011) revealed that only 9% of the papers published were for tropical cities.

One of the earliest UHI studies in warm, humid cities was conducted by Nieuwolt in Singapore. (Nieuwolt, 1966). Since then Jauregui (Jauregui, 1993; 1996) has published two special bibliographies on tropical UHI studies.

An overview of the energetic processes of tropical UHIs was provided by Roth (2007). He found that:

> UHI intensities are generally lower compared to those of temperate cities with comparable population and show a seasonal variation with lower (higher) intensities during the wet (dry) season. The amount of net radiation dissipated by sensible heat during daytime is about 40% which is similar to values observed in (sub) urban areas of cities located in temperate climates. Energy partitioning is modulated by water availability and higher percentage of vegetation promotes latent heat flux at the expense of surface heat storage. The apparent strong influence of vegetation and water availability on the energy partitioning irrespective of the climate type, suggests vegetation to be an 'effective means to reduce heat storage uptake during daytime and hence has the potential to effectively mitigate the nocturnal heat island.'

In recent years, Hung et al, (2006) provided remotely sensed data on local climate in major tropical megacities (Bangkok, Ho Chi Minh City and Manila). Contrary to the cases in temperate cities, warm, humid cities appear to have significant urban warming during the day and the extent of urban warming appears proportional to the city size (population) (Table 2)

Table 2: UHI magnitude in selected tropical Asian megacities.
Source: Hung et al., 2006

	Bangkok	Manila	Ho Chi Minh City
Mean Rural temperature (oC)			
Day	29.5	26.5	30.0
Night	21.5	20.0	22.0
Magnitude of UHI (oC)			
Day	8.0	7.0	5.0
Night	3.0	2.0	2.0
Longitudinal extent of urban effect (km)			
Day	33	25	25
Night	30	20	20
Latitudinal extent of urban effect (km)			
Day	48	45	22
Night	40	30	15
Footprint area of urban effect (km2)			
Day	1243	883	431
Night	942	471	236
Population (millions) in 2000			
	11	9.93	6.5

Kataoka et al. (2009) compared the observed temperatures in major Asian cities to that of the gridded temperature from four grids surrounding these cities. Up to 2^{o}C warming can be seen in many tropical / sub-tropical Asian cities and the trends in urban warming have accelerated in recent years. Tokairin et al. (2010) found that in Jakarta the sea breeze developed at an earlier time of day compared to 40 years ago and a converging flow developed over the city core. This together with the advection of heat from the surrounding area led to 77 Wm^{-2} of heat (equal to 44% of the sensible heat flux from the ground surface into the atmosphere). Another remotely sensed tropical UHI study conducted in Manila, Philippines (Tiango et al, 2008) indicates cliffs and plateaus in local temperature and these were related to the amount of green cover. (Emmanuel et al, 2011)

2.4 Urban Heat Island studies in Colombo, Sri Lanka

Colombo's Urban Heat Island is well documented, especially by Emmanuel. Emmanuel (2004), examined the historic trends in thermal comfort in the Sri

Lankan primate city of Colombo and correlated them with land cover changes. The land cover was calculated from time-series aerial photographs in terms of “hard” cover (buildings, paved areas and roads) and “soft” cover (trees, green areas and bare lands). The period selected for analysis included pre-rapid (up to 1977) and rapid urban phases (1978 onwards) in the city. (Emmanuel, 2004) It was found that an increase in the hard land cover, reduced the level of thermal comfort, particularly at night-time. This factor was seen to be significant, especially at the suburban station. The relative importance of land cover in city centre vs. rural areas was clearly visible. Hard cover had more effect on thermal discomfort in city centre than in rural areas.

Emmanuel and Johansson (2006), analysed the “influence of urban morphology and sea breeze on the microclimate of Colombo”. Five urban measurement sites were chosen together with a corresponding rural site. (Fig. 8)

They found that:

- Temperature differences between the urban sites reached 7 K on clear days in spite of the relatively wet period of measurement.
- Urban morphology had a significant impact on daytime air temperatures
- Maximum daily temperature decreased with increasing H/W ratio.
- The effect of Sea breeze was evident
- Sites open to the sea were significantly cooler than other urban sites.
- In contrast to the daytime variations, only small intra-urban temperature differences were found at night.

While the 2006 study examined existing sites of differing morphology, Emmanuel and Fernando (2007), used a micro-`scale urban simulation program, ENVI-met, to compare Colombo, Sri Lanka and Phoenix, Arizona, USA. The study examined - “the sensitivity of air temperature and mean radiant temperature (MRT) of built-up urban cores to urban-area geometry (the density of buildings), thermal properties of human-made surfaces (albedo) and green cover (street trees)”. Air temperature and MRT are indicative of human thermal comfort, and their rural/urban gradients signify the urban heat island (UHI) effect. It was found that, “although high albedo values lead to low daytime temperatures in both cities, the best thermal comfort, quantified by both the air temperature and MRT, was found in a more high-density development. Thus, density enhancement is a viable UHI mitigation option in built-up areas of warm climate cities". (Emmanuel & Fernando, 2007)

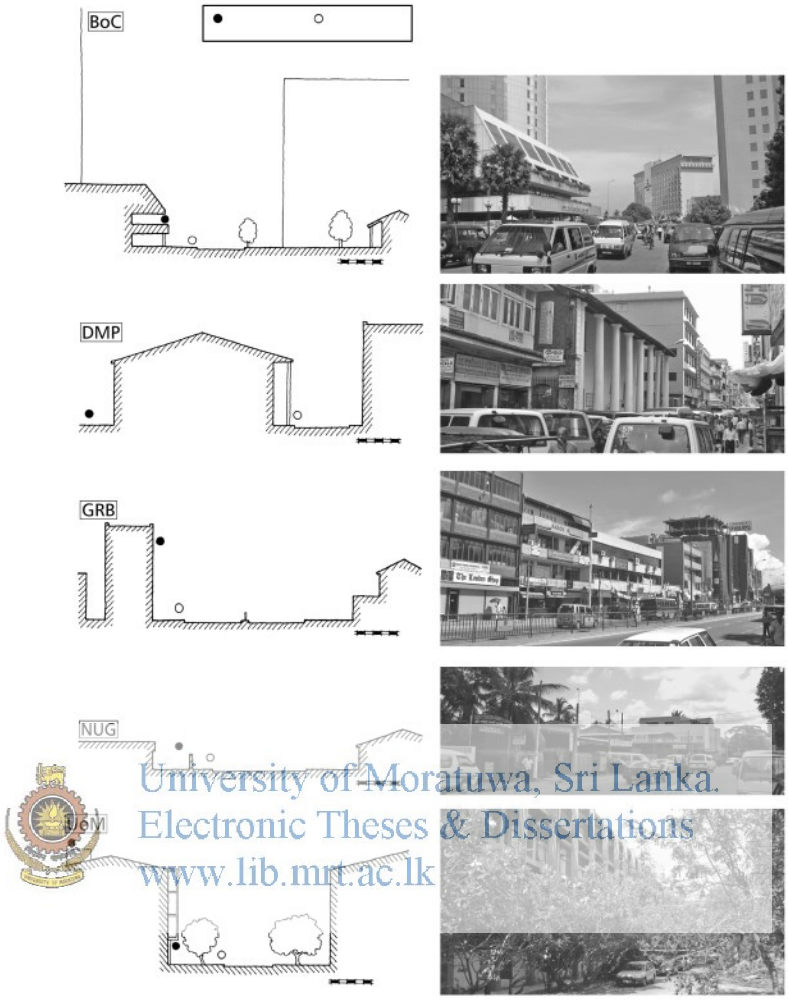


Fig. 8 - Positioning of measurement equipment within urban canyons.
(Source: Emmanuel et al, 2006)

2.5 Design strategies to ameliorate urban warming in warm, humid cities

This section reviews the approaches to mitigate and adapt to the negative effects of UHI. This is deemed the next steps in the sequence to create climate sensitive urban spaces, as an application agenda for acquired knowledge in the area, especially in the tropics.

Grimmond et al. (2010) establish that:

> Without cool winters, urban populations in tropical regions may be exposed year-round to the negative consequences of urban warmth. Ventilation is

critical in the tropics. Designs, through manipulation of geometry (height and width of buildings, building and street orientation and street width) have to consider ways to increase wind penetration and provide shade during thermally critical times of the day to enhance thermal comfort (Emmanuel, 1993, 2005; Ng et al., 2006, 2009). The high zenith sun angles in the tropics require a combination of building heights and geometry with elements such as canopies, awnings and vegetation. The time when shading is beneficial depends on the general weather pattern in the tropics, the typical dimensions of city blocks in a particular city and people's activity patterns (Lam et al., 2008).

The abundance of natural vegetation in the humid tropics can be utilized to provide shade and evaporative cooling. At high zenith angles roofs are the most thermally active building surface. Vegetated roofs can enhance thermal comfort by insulating buildings, and can improve air quality, reduce storm water runoff intensity, improve run-off water quality and create new habitat for wildlife, and hence have been used extensively in many climatic regions (Rosenfeld et al., 1998; Rosenfeld et al., 1998; Onmura et al., 2001; Köhler et al., 2002; Brenneisen., 2003; Wong., 2003; Kumar et al., 2003; Saiz et al., 2006; Kosareo et al., 2007; Mentens., 2006; Carter et al., 2007). Similarly, vegetation provides thermal benefits, removes air pollutants and absorbs CO_2, relieves human stress, mitigates run-off intensity during storms and modulates urban flood events.

The design strategies to ameliorate urban warming in warm, humid cities can be grouped into four focus areas;

a. Manipulate urban geometry to shade
b. Promote the urban wind flow for thermal comfort and pollution dispersal
c. Increase vegetation cover
d. Increase thermal reflectivity (albedo) of urban surfaces

a. Manipulate urban geometry to shade

Evidence from the warm, humid tropics as well as from cities with warm, humid summer conditions indicate that shade (either caused by buildings or trees) to be the single most important design parameter in determining local warming/cooling, as the radiative flux from direct sunlight has a strong influence on the heat balance of the body. (Taylor & Guthrie, 2008)

In the high-density settings of Hong Kong, Yang et al. (2011) found that on a diurnal basis, 'the semi-enclosed plot layout with high density and tree cover has the best outdoor thermal condition.' Tan et al. (2013) found in Singapore, that the effect on MRT is significant by shade cast by trees and buildings during daytime and does not differ considerably in the absence of sunlight. Therefore, any attempt at lowering the MRT should logically be done only in daytime. (Tan et al., 2013) Similarly, an annual outdoor thermal comfort study in Taiwan (Hwang et al., 2011) found that outdoor thermal comfort is best when a location is shaded during spring, summer, and autumn. Whether the shade comes from trees or shading devices make little difference. Noting the benign neglect of street level shading in contemporary urban planning and design in hot climates Erell (2008) states that in hot climates with high radiant loads, net radiant balance may be more important than convective exchange. This has greater effect on pedestrian comfort than the minor modifications to air temperature usually reported in street level measurements. (Emmanuel et al, 2011)

The worst street-level comfort conditions in warm, humid regions are associated with wide streets lined with low-rise buildings and no shade trees (Erell, 2008). The most comfortable conditions are associated with narrow streets and tall buildings, especially if shade trees are also present. (Emmanuel, 2011)

The "Shadow Umbrella"

An urban approach to shade enhancement was first proposed by Emmanuel (1993). The concept, called "shadow umbrella" utilises the urban massing to shade the areas between buildings. Emmanuel (2005) details the procedure and presents design strategies derived from this concept.

The fundamental step in arriving at such a 'shadow umbrella' is to establish the shadow angles. In order to develop an urban massing that can shade itself depends on the following factors; Date of the year; Time of the day; Location; Building/site orientation and dimensions. (Emmanuel, 2005)

In the case of tropical regions, the sunrays reach from all directions, including north and south. The northern-most solar exposure occurs during the summer solstice (June 21 or thereabouts) and the southernmost exposure will be on the winter solstice (December21 or thereabouts). While these two days determine the northern and southern extremities of sun positions, respectively, cut-off times on each of these days determine the eastern and western extremities. (Emmanuel, 2005)

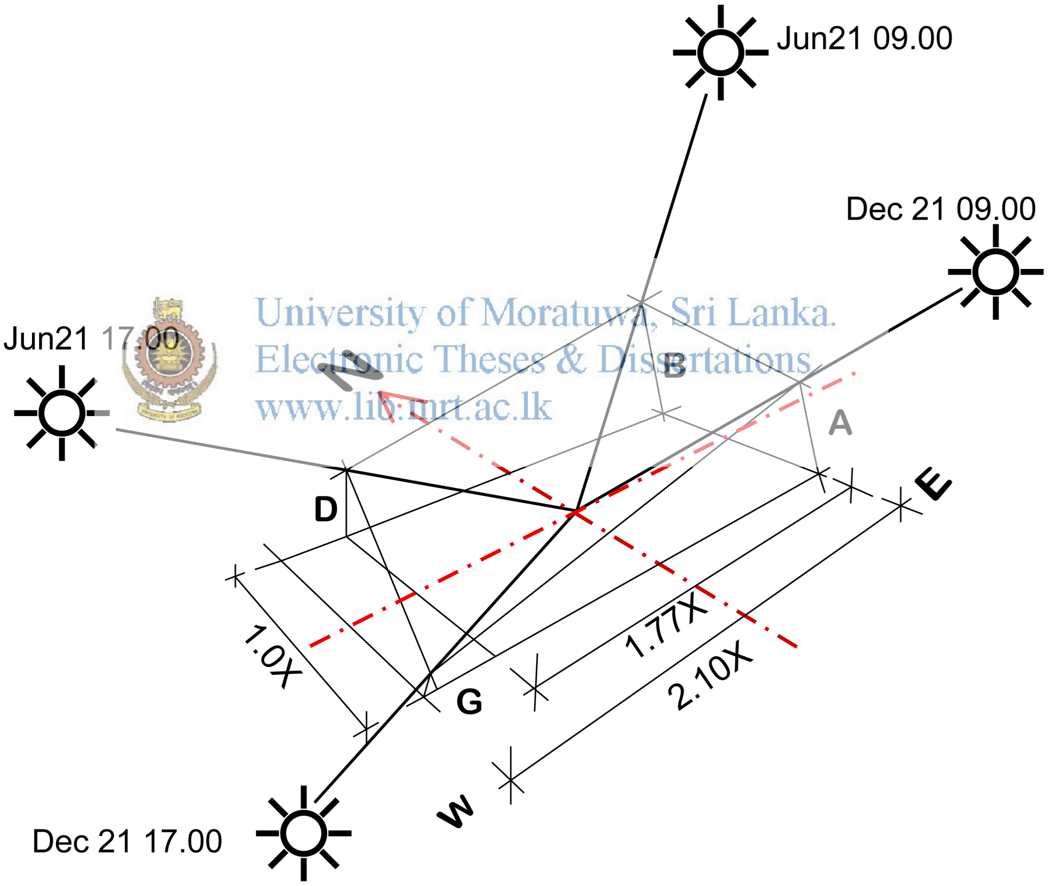


Fig. 9 - An ’ideal’ shadeable urban block. (Source: Emmanuel, 1993)

With the establishment of the times at which shading is to be provided, the four corners of a perfectly shaded commercial city block, for example, can be determined. Fig. 9 shows how these four positions of the sun (09.00 hrs. on June 21, 17.00 hrs. on June 21, 09.00 hrs. on December 21 and 17.00 hrs. on December 21) can be developed into an 'ideal' shadeable urban block. The sloping planning the figure is the 'shadow umbrella'.

Emmanuel (2005) summarises the generic approach detected from the 'shadow umbrella' as follows;

- Buildings will be tall on the north and east
- Buildings on the west will be the smallest
- It is preferable to leave a wide margin on the western side of the block. This space can be used to plant trees, etc., that could offer additional shading.
- The centre of the block can be left open. This opening can be either parallel to the north/south sides of the block, or a U-shaped court.

b. <u>Promote the urban wind flow for thermal comfort and pollution dispersal</u>

Ventilation has been a key strategy for thermal comfort and pollution dispersal in hot climates from ancient times. However, the low levels of wind speeds in the tropics due to the passing of the inter-tropical convergence zone twice a year makes it necessary to carefully map out the ventilation strategy at a city-wide level to induce sufficient air movement, both for pollution dispersion as well as thermal comfort. It will also enhance the cooling potential of naturally ventilated buildings (which is the most common approach to indoor cooling in the warm, humid tropics). Hong Kong's approach to a citywide ventilation strategy via the 'Air Ventilation Assessment' (AVA) method (Ng, 2009) best exemplifies such a planning assessment method. (Emmanuel, 2011)

Ng (2009) suggested that ventilation strategies for pollution dispersal and thermal comfort need to consider both city-wide as well as street-level measures such as breezeway/path (city wide scale); building plot coverage, building orientation relative to streets, heights of building in relation to one another and building permeability.

Streets can be oriented along the prevailing wind directions to provide a constant low speed aeration path. To enhance the ventilation in the streets perpendicular to the prevailing wind directions, wider streets (lower H/W) or higher buildings on the downwind side of the street to encourage downdraughts can be used. Alternatively, wind-catching structures can draw wind into these streets. (Taylor & Guthrie, 2008)

Chan et al. (2001) found that non-uniformly building heights provide better ventilation and tall buildings do not necessarily promote blockage. A wider canyon promotes better mixing of air and canyon geometry should be restricted to threshold value for skimming flow and maximum relative canyon length to height ratio - L/H - should be kept at five. (Ali Toudert, 2005)

Another strategy to induce street-level ventilation is to use the differences in surface temperatures of vertical surfaces of buildings in high-density areas. For example, Yang and Li (2009) found that the surface temperatures of walls in high density Hong Kong increases with height during the day and reverses at night, leading to ventilation induced by thermal buoyancy that could be 2-4 times stronger than mountain slope flows. (Emmanuel et al, 2011)

c. Increase vegetation cover

The importance of urban greenery to human comfort at street level is long recognised. However efforts to use greenery to ameliorate urban warming need to be cognizant of the scale of the effect due to different kinds of greenery, limitations of its use and the unintended consequences that might arise by their haphazard deployment. (Emmanuel, 2011)

Urban greenery to tackle local warming in warm, humid cities may take the form of green roof, green walls, surface green (such as lawns) or street trees. Although the effects of green cover manipulations on street level air temperature remains muted, its effect on thermal comfort is significant. (Emmanuel et al., 2011)

The results of studies in Beijing, China by Zhao et al., 2010, indicate that mesoscale urban planning indicators can explain the majority of the urban climate differences among the sites considered. For example, green cover ratio and floor area ratio can explain 94.47 to 98.57% of the variance for daily maximum surface temperature, green cover ratio and building height can explain 98.94 to 99.12% of the variance for daily minimum surface temperature, and floor area ratio, green cover ratio and building density together can explain 99.49 to 99.69% of the variance for time of peak surface temperature. Furthermore, green cover ratio is identified as the most significant urban planning indicator affecting the urban thermal environment. (Zhao et al, 2011)

Perhaps a meta-review conducted by Bowler et al., (2010) on the purported effect of urban greenery best sums up the findings to-date. Noting the nature of observational studies on urban green effect (small numbers of green sites), Bowler et al., (2010) concluded that 'the impact of specific greening interventions on the wider urban area, and whether the effects are due to greening alone, has yet to be demonstrated.' Further empirical research is necessary in order to efficiently guide the design and planning of urban green space, and specifically to investigate the importance of the abundance, distribution and type of greening. It is also necessary to be mindful of the interference urban greenery could cause to street-level pollution removal, especially on the leeward side of urban canyons (Gromke et al., 2008; Salim et al., 2011) as well as the enhanced water use that might be required to maintain the green cover (Gober et al., 2010). (Emmanuel, 2011)

d. Increase thermal reflectivity (albedo) of urban surfaces

Extensive use of high-albedo materials has been advocated as a means of mitigating the urban heat island, especially in warm-climate cities. The implicit assumptions of this strategy are that by lowering canopy layer air temperature, cities will enjoy a) reduced air conditioning loads in buildings and b) improved thermal comfort for pedestrians in outdoor urban spaces. (Erell et al., 2012)

In the typically low wind speeds prevalent in tropical cities, the effect of facade materials and their colours assume greater significance. Priyadarshani et al. (2008) found that low albedo facade materials in Singapore led to a temperature increase of up to 2.5°C at the middle of a narrow canyon. Emmanuel and Fernando (2007) found that high albedo could make sunlit urban street canyons up to 1.2°C cooler in Colombo, Sri Lanka.

However, it is important to keep in mind that albedo enhancement strategies, like urban greening, are more likely to show improvements in air temperatures than thermal comfort (Emmanuel et al., 2007). From an urban design point of view, mitigation options ought to focus on thermal comfort enhancement (including the MRT) rather than merely attempting to control air temperatures (Emmanuel & Fernando., 2007).

Erell et al., 2012 cautions, 'although use of high-albedo materials in urban surfaces may reduce the air temperature to which pedestrians are exposed, this change has only a small effect on their thermal balance with the environment: The reduction in surface temperatures, which leads to reduced long-wave emission, is offset by increased reflection of solar radiation. The net effect of increasing the albedo of urban surfaces may thus be a small increase in the thermal stress to which pedestrians are exposed – rather than the expected improvement in thermal comfort'.

Yet, in other contexts, highly reflective surfaces have resulted in extreme overheating in adjacent buildings and surfaces. Futcher and Mills (2014), writing on the context of London, "too many buildings are being designed without due consideration of their impact on the wider built environment. Minds have been concentrated on the issue by the impact of 20 Fenchurch Street -aka the walkie-scorchie - on its neighbours when light reflected by its concave glass façade scorched buildings and objects.

2.6 Climatic maps, developing urban climatic guidelines, and implementing mitigation measures for local planning practices

"Facing the global issue of climate change, it is also necessary to include the changing climatic considerations holistically and strategically in the planning process, and to update city plans." (Ren et al., 2010)

Urban Climate Map (UCMap)

The urban climatic map (UCMap) is an information and evaluation tool to integrate urban climatic factors and town planning considerations by presenting climatic phenomena and problems into two-dimensional spatial maps (Baumüller et al., 1992; VDI, 1997; Scherer et al, 1999).

It consists two major components:

Urban Climatic Analysis Map (or Synthetic Climate Function Map) (UC-AnMap)

Fig. 10 demonstrates the information layers that are a part of the UC-AnMap. The analytical map brings together, climatic elements; geographic terrain information; greenery information; and planning parameters in a GIS (Geographic Information System) based platform.

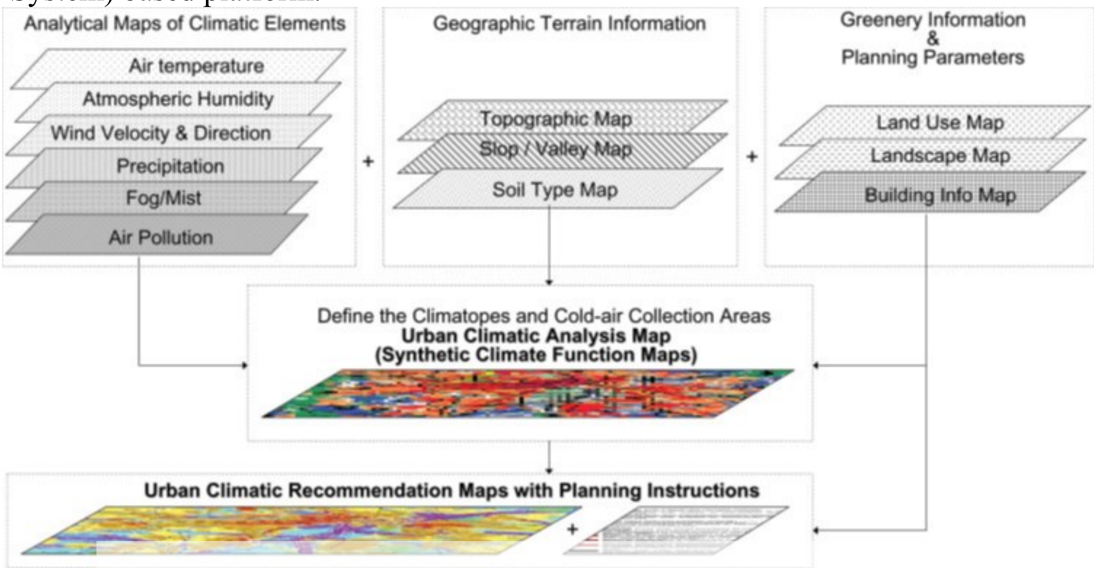


Fig. 10 - UC-AnMap and UC-ReMap. (Source - Baumüller et al, 1992 as cited in Ren 2010)

Urban Climatic Planning Recommendation Map (UC-ReMap).

The UC-ReMap is an integrated, planning-action-oriented assessment base that could be operated at the city or the district scale. On the basis of the analysis obtained from the UC-AnMap, similar climatopes are grouped into zones to present the sensitivity of certain land areas affected by land use changes. (Ren et al. 2010).

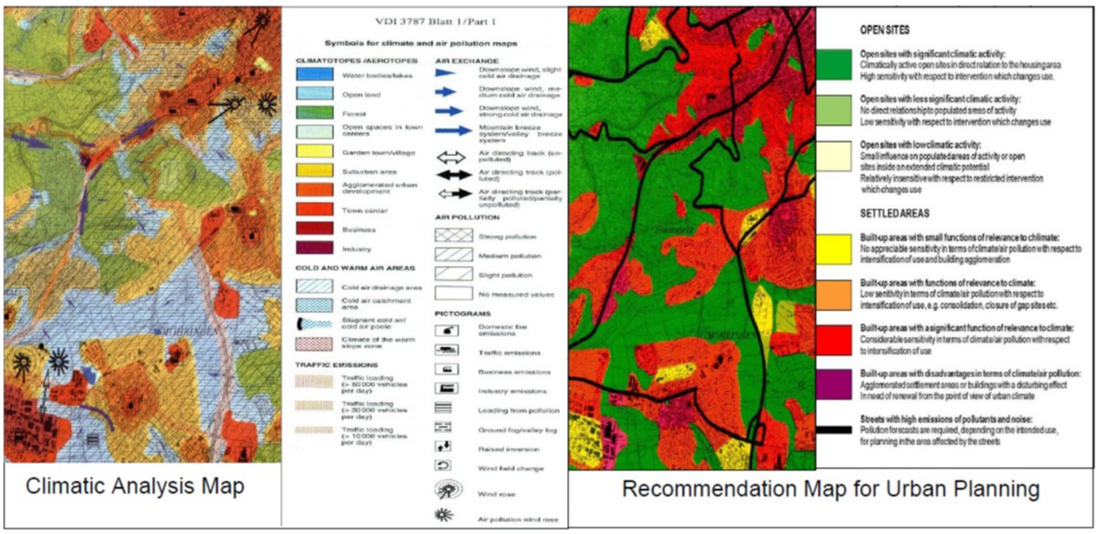


Fig. 11 - UC-AnMap and UC-ReMap. (Source - Baumüller et al, 1992 as cited in Ren 2010)

Fig. 11 shows an example for the two maps by Baumuller (1992). It highlights problem and climate sensitive areas in the city that a multi-disciplinary teams need take heed of, for development and amelioration.

The UCMap system has been adopted by many cities around the world. A comprehensive review is seen in (Ren et al., 2010).

Among many advantages of the system the main disadvantages, in relation to the current study is seen in the need for future studies to focus on climate change impacts, recommendation maps that incorporates such concerns and in the context of extensive data and data collection regimes needed for the analysis maps,

<u>Local Climate Zones</u>

The new "Local Climate Zone" (LCZ) classification system provides a research framework for urban heat island studies and standardizes the worldwide exchange of urban temperature observations. (Stewart & Oke., 2012) It was developed to help to fill a crucial void in UHI methodology; the lack of an accepted protocol to gather and report heat island observations in the canopy layer.

"Such a protocol should build on existing guidelines, conventions, and frameworks in urban climatology. The LCZ system does that, and provides a simple division of urban and rural landscapes into morphological classes, from which a standardized definition of heat island magnitude is derived. This approach moves the field closer to a cohesive and workable set of 'rules' to assess UHI magnitude in the canopy layer and to allow objective comparisons of UHI magnitudes in different cities". (Stewart & Oke., 2012).

Detailed in Table 3, are recent studies using the LCZ system for Mapping, Siting of data collection points, Comparative studies and thermal comfort, among other applications. The strength, therefore, the growing use of the system lies in the "comprehensive nature of the classification system with its thorough coverage of all likely urban land use/land cover classes meaning that a given LCZ class is comparable across many different cities". (Stewart, 2011)

Table 3 - Previous work using LCZ classification as the primary tool

Author(s), year	**City**	**Parameter(s) studied**
Mapping and UHI Studies		
Villadiego and Velay-dabat, 2014	Barranquilla, Colombia	Thermal comfort, thermal sensation.
Perera *et al*., 2012	Colombo, Sri Lanka	UHI.
Perera *et al*., 2013	Colombo, Sri Lanka	UHI.
Perera and Samanthilaka, 2014	Colombo, Sri Lanka	UHI.
Middel *et al*., 2012	Phoenix, AZ	Daytime cooling efficiency and diurnal energy balance. ENVI-met.
Middel *et al*., 2014	Phoenix, AZ	Urban form, landscaping and air temperature.
Emmanuel and Loconsole, 2015	Glasgow, Scotland	Mapping, ENVI-met, air temperature, surface temperature, thermal comfort. Green infrastructure for overheating adaptation.
Bechtel *et al*., 2012	Hamburg, Germany	UHI. Remote sensed classification. GIS.
Acero *et al*., 2014	Multiple cities	Mapping/comparative database for climate change impacts.
Unger *et al*., 2014a	Szeged, Hungary	Mapping. GIS.
Alexander and Mills, 2014	Dublin, Ireland	*In situ* stations and mobile traverses. Land-cover / land use maps as basis.
Siting of Weather Stations		
Siu and Hart, 2013	Hong Kong, china	LCZ for classification of weather-station siting.
Wong, 2014	Hong Kong, China	LCZ for classification of weather-station siting. Remote sensing and GIS.
Peng and Jim, 2013	Hong Kong, China	LCZ for classification of weather-station siting. ENVI-met. Green roofs on UHI.
(Thomas *et al*., 2014)	Kochi, India	UHI. Mobile traverse.
Grimmond, 2013	London, UK	
Leconte *et al*., 2014	Nancy, France	UHI. Mobile measurement method.
Historical/Comparative Studies		
Hebbert, 2014		A historical perspective on similar systems.
Scherer and Endlicher, 2014		A historical perspective on similar systems.
Thermal Comfort/Climate Change/Vulnerability Impact Studies		
Puliafito *et al*., 2013	Mendoza, Argentina	PET, air temperature. Green roofs, mobile measurements.
Perera and Langappuli, 2013	Colombo, Sri Lanka	MRT.
Perera and Weerasekara, 2014	Colombo, Sri Lanka	MRT. Outdoor thermal comfort.
Müller *et al*., 2013	Oberhausen, Germany	Climate change adaptation, PET, ENVI-met.
Dubois *et al*., 2012	Quebec City, Canada	UHIE, urban indicators, climate change adaptation, air temperature, ENVI-met.
(Kaveckis and Bechtel, 2014	Hamburg, Germany	Urban vulnerability assessment framework. Uses Metronamica, a raster-based land-use model, which uses cellular automata (CA).
LCZ validation		
Coseo and Larsen, 2014	Chicago, IL	Used LCZ urban variable measures to match eight Chicago neighbourhoods to LCZ classes.

An exemplar approach is adopted by WUDAPT (World Urban Database and Access Portal Tools), where the primary objective to "develop a database that uses consistent descriptors and gathers information at a suitable scale" (WUDAPT, 2014b)

The World Urban Database and Access Portal Tools (WUDAPT) is an initiative to collect data on the form and function of cities around the world. The impact of cities on the climate at urban, regional and global scales is a topic of considerable debate. Much of the relevant research to date has been focused on mapping urban centres using demographic and administrative information, often supplemented by remote sensing. However, these data provide no information on the internal make-up of cities, which is important for understanding their impact on the environment as well as their vulnerability to change. The most recent report from the Intergovernmental Panel on Climate Change (IPCC) notes the dearth of information on urban areas. The WUDAPT initiative is designed to fill this gap. (WUDAPT, 2014a)

The LCZ scheme is integral to the process. The WUDAPT protocol is based on the classification of cities using LCZs and then developed using remote sensed applications with vital local knowledge in classifying and validating training data needed.

LCZ classification plays a pivotal role in this thesis. Where its application in the experimental context of Colombo establishes the needed impetus for developing strategies for planning and policy.

<u>Urban design and planning strategies</u>

Urban design and planning strategies targeting the amelioration of urban warming in warm, humid cities are rare. It is even rarer to see an explicit link being made with urban warming strategies and the adaptation to global/regional warming in the region. (Emmanuel et al., 2011)

A global survey of Urban Sustainability tools were presented by Criterion Planners (2014) (Fig. 12). The survey exemplifies the dearth of initiatives in the tropical regions.

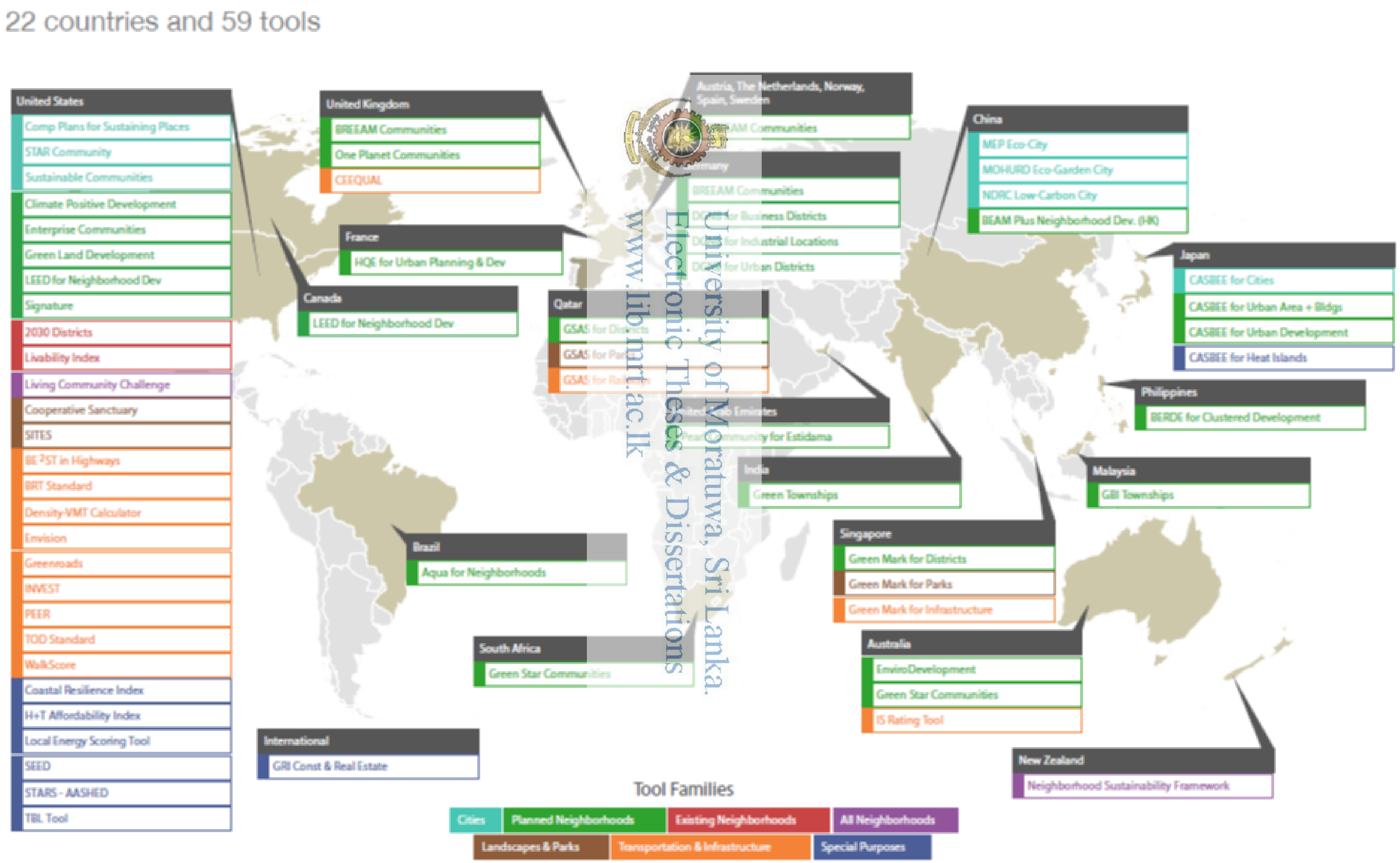


Fig. 12 - Global Survey of Urban Sustainability Tools (source - Criterion Planners, 2014)

Exemplar efforts among cities with warm climates for UHI mitigation and global-warming adaptation is seen for Japanese cities. The policy framework, termed; Comprehensive Assessment System for Built Environment Efficiency (CASBEE), approach the problem from the scale of the individual to the city scale. (Fig. 13)

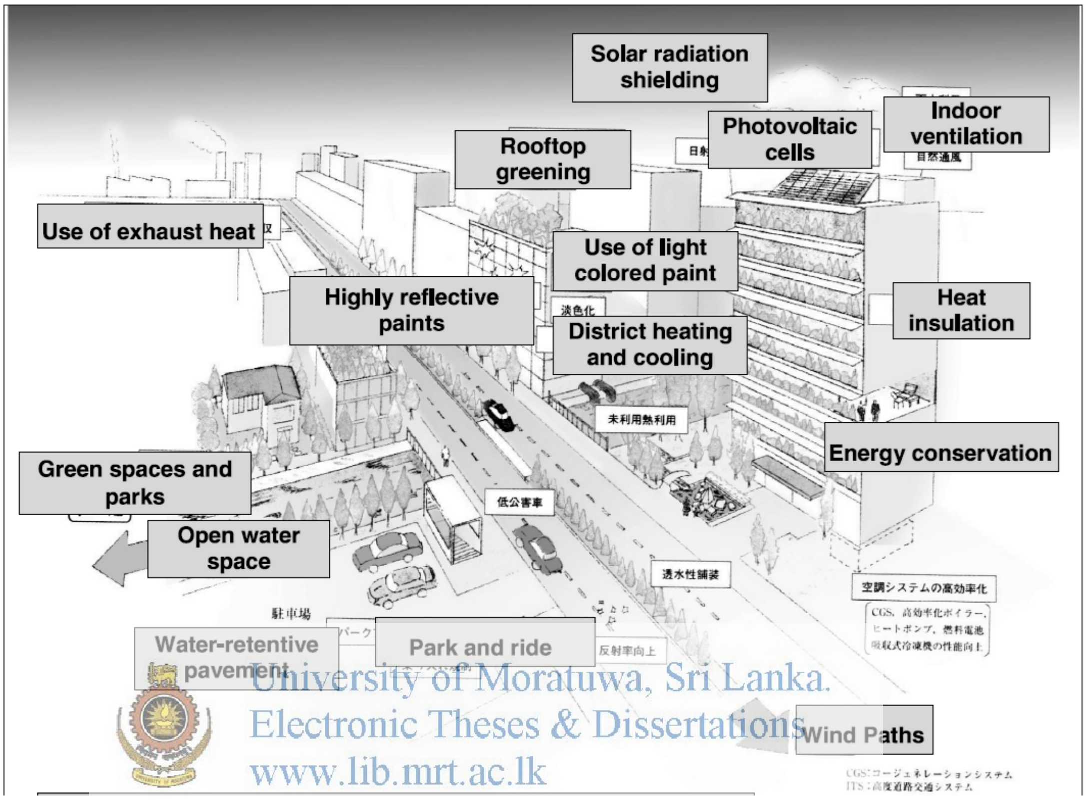


Fig. 13 - Major urban heat island mitigation measures. (Source: Yamamoto 2006)

Japan's 'Outline policy framework to reduce UHI effects' adopted in March 2004 (cited by (Yamamoto, 2006)) aims to:

1. Reduction in anthropogenic heat release (reduction and substitution)

- Building and plant energy efficiency
- Building insulation and shade
- Greening of buildings
- Reflective surfaces
- District cooling systems and reuse of waste heat

2. Improvement of artificial surface covers (reduction of sensible heat transfer and expansion of latent heat transfer)

- Reflective pavements and water retention
- Green cover and open spaces

3. Improvement of urban structure (improvement and integration of advection currents)

- Building morphology and land use manipulation
- Greenery

2.7 Research Gaps

As stated at the start of this chapter, the literature review is extended to Chapter 3 - Research Design, especially to encompass work done using the LCZ system and ENVI-met. Each of these major components of this thesis is explored in terms of morphology - climate links. The separation of the two chapter elements are envisioned as two-parts of the same approach - the theory (Chapter 2) and the application (Chapter 3) - both essential to the discussion.

In relation to the above - research gaps - are identified and explored as the core issues in this thesis.

<u>Protocols for LCZ deployment in data- scarce tropics</u>

The LCZ system was developed as a set of protocols that allow more meaningful reporting of the UHI phenomenon, across cities of different geographies and climates. In recent studies, the LCZ scheme has gained acceptance as means to use observational data for classification and mapping. The ability of the system to be applied quickly - in a data scarce context - is seen as one of its main advantages.

The establishment of a set of protocols for the deployment of LCZ as the base data - - needs to be explored.

This links to the primary research problem - “lack of a strong morphological and climatic base for urban design, planning and policy to be established upon - in the warm humid tropical settings".

Further, the research question of - **"What is the microclimatic background condition that climate sensitive urban policy needs to be based upon"?** - is derived from this research gap.

Sensitivity analysis of what are key design parameters for the mitigation of UHI and outdoor thermal comfort in the tropics

The primary aim of the thesis is to create climate sensitive urban public spaces by exploring urban design-climate links. Therefore, the task encompasses both factors - thermal comfort in the urban outdoors and climatic effects of such strategies on the local warming (UHI). Mean Radiant Temperature (MRT), as opposed to air temperature is used as the measure for the analysis.

Research that brings together morphology and UHI have been explored extensively. Similarly, the microclimate and morphology. Sensitivity analysis of urban variables on these factors have been dealt with.

The exploration of the sensitivity of urban indicators for both thermal comfort and UHI amelioration - in a future background climate warmed by global warming - needs consideration.

The research question of;

What are the key urban morphology variables (Geometric and Surface Cover) that will define and drive the decision making process, at both the existing as well as a warmed urban microclimate? - is derived from this research gap.

Conversion of findings into planning strategies

Conversion of research findings in terms of microclimate and morphology into planning and policy is rare, especially in the warm humid tropics. A majority of the studies stop at the theory and do not translate into planning and policy. Most draw conclusions on the existing background conditions, both physically and climatically.

Further, research explores the basic element of the "urban canyon' in most morphology-microclimate studies. A consideration of the planning / precinct / block scale needs consideration.

Studies that look ahead to an urban context affected negatively by global warming are deemed necessary.

The research question of;

What are the planning and policy implications that can be generated to adapt to or roll-back the negative effects of a warmed urban microclimate? - is derived from this research gap.

Similar study approaches in literature

Several researchers highlight the significance of the research gaps discussed above. The introduction to the research problems and literature pertaining to the same were discussed in Chapter 1, where writings of Mills, Oke and Emmanuel set the stage for further exploration of the topics.

Grimmond et al, 2010 in a needs analysis for Climate and more Sustainable cities highlight the following, (among other factors), are deemed directly relevant to the this research;

<u>Data</u>

- Need to meet data requirements to allow translation of research findings into urban/building design tools and guidelines for different climate zones and classes of urban land use.
- Need to ensure that data are provided in a format that is usable for a broad range of practitioners without compromise to scientific accuracy and integrity.
- Need to ensure metadata to describe instrument, siting, quality assurance and control features and documentation are complete and comparable by creating and using a standardized urban protocol.

<u>Tools</u>

- Need to develop tools to allow models to be able to accommodate the wide differences in data availability depending on the application from research to operational situation.
- Need to develop tools that allow competing and unintended impacts of proposed sustainable design to be assessed (for example, will urban greening reduce temperatures but increase humidity, resulting in no net increase in comfort levels?).

Masson et al, (2014), explore a similar study for Toulouse, France, where they explore " Adapting cities to climate change: A systemic modelling approach". A crucial area highlighted is in the approach to "Impact assessment" by the use of "indicators". The interdisciplinary approach used here allows a wide range of evolution paths and impacts to be considered and assessed. The indicators used for assessment are based on both the data provided to create the scenarios (results from the participatory approach and data necessary as input to the models) and data simulated by the different models. Some indicators may be a mix of these two. The major indicators that were estimated for each adaptation strategy and climate warming scenario are; Economic and socio-economic indicators; Urban form indicators; Micro-climate and comfort indices; Energy consumption indicators.

Summary

The chapter explores critical concepts in literature to highlight research gaps and develop research questions.

The research questions are highlighted as;

- "What is the microclimatic background condition that climate sensitive urban policy needs to be based upon"?
- What are the key urban morphology variables (Geometric and Surface Cover) that will define and drive the decision making process, at both the existing as well as a warmed urban microclimate?
- What are the planning and policy implications that can be generated to adapt to or roll-back the negative effects of a warmed urban microclimate?

These questions establish the primary topics in the Research Design in the next chapter.

3.0 Research Design

3.1 Introduction to the chapter, the research design and Colombo, Sri Lanka as a case study

The main aim of the research is in **bridging the gap in urban design-climate links, being translated into guidelines for real-world applicability** for the **warm humid tropical** climate of **Colombo**, **Sri Lanka**, in a background climate affected by **Global Warming**.

The research design is focussed in answering the three main research aims / questions detailed out in Chapter 1.3;

1. What is the microclimatic background condition that climate sensitive urban policy needs to be based upon?

2. What are the key urban morphology variables (Geometric and Surface Cover) that will define and drive the decision making process, at both the existing as well as a warmed urban microclimate?

3. What are the planning and policy implications that can be generated to adapt to or roll-back the negative effects of a warmed urban microclimate?

Methodological steps for each of these questions are outlined in detail in Section 3.2 and Section 3.3 in this chapter. Each of the 'process steps' generate the needed input parameters for the next step of the research process.

3.1.1 Introduction to the research design

The introduction to the chapter is further elaborated by addressing each research question, its constituent components and culminates by tabulating as a matrix the process steps together with the methods adopted to reach its objectives.

1. What is the microclimatic background condition that climate sensitive urban policy needs to be based upon?

a. What is the existing and therefore the predominant urban fabric morphology of the city of Colombo?

b. What is the comparative microclimatic effects of such a morphology in terms of 'Local Warming'?

Encompassed in **Section 3.2** of this chapter - **"Classifying, Simplifying and Understanding the Climatic Context - for Colombo, Sri Lanka",** it approaches these questions by adopting the following steps as a process where the data generated from the preceding section, generates the needed input for the next.

	Process "Step"	Method
3.2.1	Classifying "Local Climate Zones"	LCZ classification system
3.2.2	Classifying "Local warming effects" of the urban fabric	SHIM (Surface Heat Island Model) application
3.2.3	Detailed categorisation of the mapped local level urban climate characteristics effecting Colombo	Analysis of data generated in previous sections
3.2.4	Analysis and discussion. Establishing the focus for further study.	

2. What are the key urban morphology variables (Geometric and Surface Cover) that will define and drive the decision making process, at both the existing as well as a warmed urban microclimate?

a. Which of the variables are most sensitive to effecting Mean Radiant Temperature (MRT)

Section 3.3 - " Computer Simulation of climatic contexts - existing and modified building morphology - using ENVI-met " - In this the second part of the process, the critical LCZ typology identified in the first section, are modelled using the computer simulation software ENVI-met. The simulated cases explore existing and projected morphology changes in the existing climatic context as well as for the projected 'global warming' perspective.

	Process "Step"	Method
3.3.1	ENVI-met - the model, Input variables, output possibilities, Limitations and validation	A comparison of on-site measurement of climatic data with ENVI-met simulation.
3.3.2	Simulation Matrix - Site definition, existing and projected morphology	ENVI-met simulation Explores series of urban morphology options to both establish variable sensitivity and gain insight into the amelioration possibilities. Thus, links to the third question relating to "implications".
3.3.3	Analysis Protocol	Statistical analysis using IBM SPSS (Statistical Package for the Social Sciences) software.

3. What are the planning and policy implications that can be generated to adapt to or roll-back the negative effects of a warmed urban microclimate?

The third research aim is in the interpretation of the findings into applicable planning and policy. This is dealt with in detail in Chapter 5. The needed impetus for such analysis and discussion is encompassed in the "simulation matrix" of morphology options in varying background climatic conditions. (Table 14)

3.1.2 Introduction to Colombo, Sri Lanka as a case study

Colombo, Sri Lanka (6°54'N, 79°52'E) (Fig. 14) is drawn upon as case study for the application of the research process. It serves as typical example of a warm humid tropical city, affected by the Urban Heat Island phenomenon and facing the negative effects of a globally warmed climate. Outlined below is an overview of the city; its geography in relation to Sri Lanka, its history, approaches to planning - historically and future projections, and its climate (existing and in a globally warmed scenario)

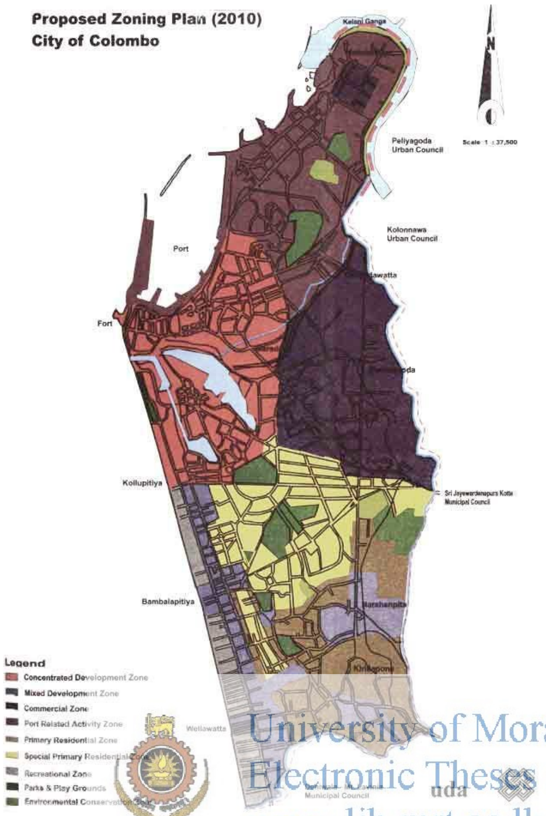
Fig. 14 - Sri Lanka and the location of Colombo. (source - www.asia-atlas.com)

Colombo, Sri Lanka's largest city, (Fig. 14) the former administrative capital and is currently defined as the financial and commercial capital of the country. Located on the country's west coast, its development was primarily based on its small seaport used by Moor, Arab, Persian and Chinese sailing vessels in ancient times. Following the occupation of the coastal provinces of Ceylon (as Sri Lanka was known in Colonial times) by Portuguese, Colombo became the centre of the Portuguese rulers and after the annexation of Kandyan Territory by the British in 1815, it became the capital of the whole island.

The Portuguese occupation of Colombo ended with the siege of 1656 when the Dutch captured the city. The Dutch occupied Colombo and other parts of the coastal Ceylon from 1656 to 1796, a period of 140 years. Thereafter, the British captured Colombo in 1796.

With Sri Lanka gaining Independence from the British in 1948, Colombo was retained as its capital city, until Sri Jayewardenepura, Kotte was named the capital city of the country in 1982.

Colombo is fast changing in terms of land use patterns and building morphology. This factor is further highlighted in the Urban Development Authority Projected Zoning Plan for 2020.



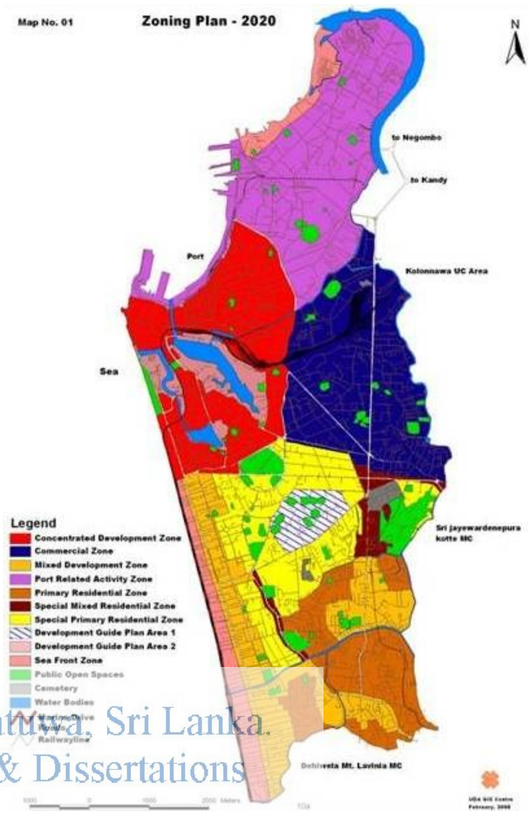


Fig. 15 - Proposed Zoning Plan (2010)
(source - uda.lk)

Fig. 16 - Proposed Zoning Plan (2020)
(source - uda.lk)

The plan for 2020 superseded the plan for 2010 with the adoption of the City of Colombo Development Plan (Amendment) of 2008. (Fig. 16) The main difference from the previous (2010) (Fig. 15) is seen in terms of the definition of the urban fabric morphology for the city. It changes from that of a 'maximum permissible height' based strategy to a 'Floor Area Ratio (FAR)' based strategy. The plan also saw a redefinition of the land use zoning together with the permissible uses within the zones. It is deemed the newer zoning allows for greater flexibility, therefore brings a certain heterogeneity to the built fabric, although the main objective seems to be to free land for development, especially in the port related activity zone.

Planning History

Brief outlines of 'Physical Plans' that have been developed for Colombo since Independence are presented here;

Patrick Abercrombie Plan - 1948 - focussed on Colombo and its surrounding regions. The main problems highlighted in the Abercrombie Plan were the high concentration of economic, trade and port related activities in the city and their effects. Decentralization of activities was one of the main objectives of the Plan. Zoning Proposals were introduced in the Plan including Character Zoning and Density Zoning. (Munasinghe, 2013)

Colombo Master Plan Project (UNDP - 1978) - moved away from the satellite town concept. A massive 100-mile linear coastal conurbation stretching from Negombo in the North to Aluthgama in the South was envisaged. (Gunaratna, 2012) The establishment of the Urban Development Authority (UDA) as a planning organization was a direct outcome of the Colombo Master Plan. (Munasinghe, 2013)

City of Colombo Development Plan - 1985 - enabled the UDA to define zoning and building regulations. The regulations, cited as the Urban Development Authority Planning and Building Regulations, 1986 (Gazette of Democratic Socialist Republic of Sri Lanka Extraordinary No 392/9 of 10th March 1986 formulated under the Urban Development authority law no. 41 of 1978 of the National State Assembly) formed the basis for development. It is still applied in areas of the island that are not covered by the subsequent plans.

City of Colombo Development Plan - 1999 - had two major advantages which the earlier plans did not: a strong environmental predication; and, considerable exposure to stakeholders, which had led to responsive modifications. (Gunaratna, 2012)

City of Colombo Development revised - 2008 - City of Colombo development Plan (amendment)-2008 is a plan to amend the City of Colombo Development Plan of 1999.

In relation to this study, the amendment plan had the following key changes to that of predecessor;

- Redefinition of Planning zones (permitted land use, relaxation of zone based building height application / restriction)
- Application of specific street widths and width between buildings (street lines and building lines for specific streets in the city)
- Redefinition of the Specifications for Development - 'Form C' to Form 'C1' and Form 'C2' of the two development plans (Building height to FAR based building regulations) (Appendix A)

Urban structure

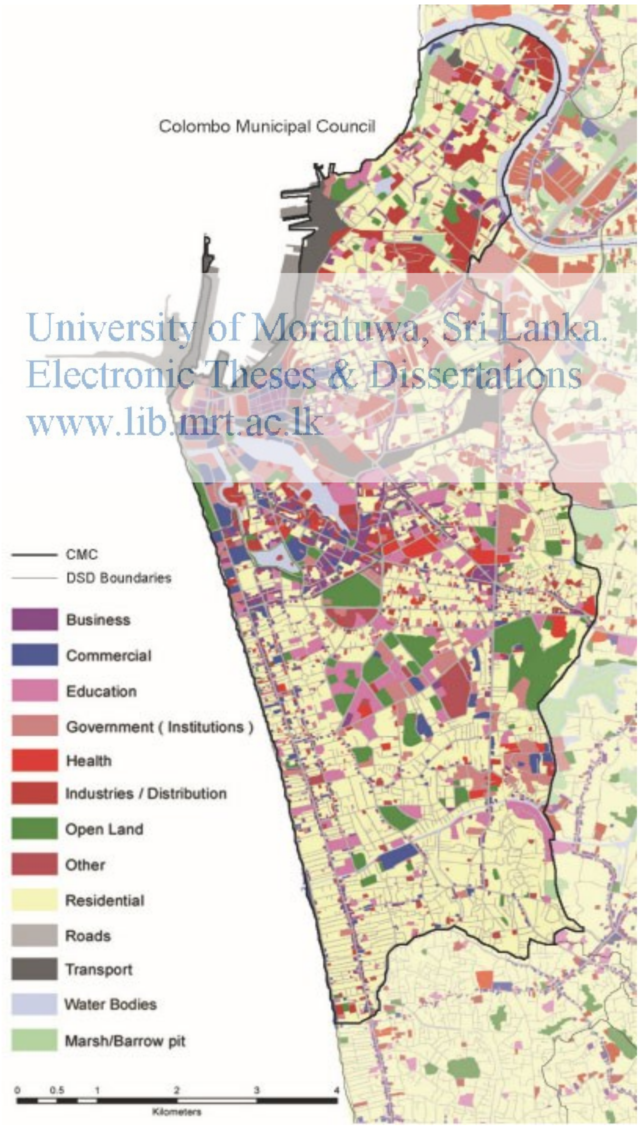


Fig. 17 - Colombo Municipal Council - Land use 2013.
Source - (JICA, 2014)

Colombo is predominantly residential. According to a survey by CoMTrans Study Team (2014), the Colombo Municipality area has over 42% residential land use, while 3.5% is commercial and 4.5% for business. (JICA, 2014)(Fig. 17) This results in an overall low building density in many areas of the city except in the central business district of Colombo Fort and Pettah. The Indian Ocean on the western edge, creates a natural limits to the city together with extensive marshlands to the east. The form of the city centres on the port and the major North / south vehicular artery - Galle Road, where the urban fabric is more mid-rise with a growing trend for high-rise developments taking hold.

<u>Climatic context - existing and future projection (A2 climate change scenario)</u>

The Köppen-Geiger classification classifies Colombo as “Af” – Tropical Rainforest Climate. Colombo is constantly moist showing no seasonal differences in terms of a dry or cold season and experiences year-round rainfall, especially with the effects of the Asiatic monsoon.

The background climate - 'Existing' climate vs. a 'Globally Warmed' climate

The primary focus of the research is to see, how the modified morphology of the built fabric can help ameliorate the negative effects of UHI in general and outdoor thermal comfort in particular. This aspect becomes even more critical for a global, regional and local context that has warmed due to the effects of global warming. In this regard, the research adopts two background climate scenarios;

Existing climate - the existing climate is interpreted as the climate that now prevalent. It is represented as the 30 year average temperature trends for Colombo. The primary data is ascertained from the ‘urban’ weather station at the Colombo City Airport (Rathmalana) (Lat: 6° 49'N; Lon: 79° 52'E; Elevation: 5m asl; WMO Station ID: 434670). This is the same data that will be used to drive the Surface Heat Island Model (SHIM) model in the next section. (Appendix D)

Future climate - This explores a background climate that has warmed due to the effects of global warming. Its particular effects are deemed evident in the local level characteristics as well. In order to establish a benchmark for such a future scenario, the research adopts the A2 projection scenario, developed by the Meteorological

Department of Sri Lanka. A2 describes a very heterogeneous world with high population growth, slow economic development and slow technological change (IPCC, 2000). The projected Year is taken as 2100.

The A2 climate scenario makes the following assumptions in its projection (Samarasinghe, 2009);

- World - Differentiated
- Economy - Regionally oriented; lowest per capita growth
- Population - Continuously increasing
- Governance - Self-reliance with preservation of local identities
- Technology - Slowest and most fragmented development

Mean Temperature Projection for 2100 - Sri Lanka

Eriyagama et al, (2010) summarised that: “There is general consensus among future projections that Sri Lanka will become increasingly warmer during the twenty-first century, although the projected magnitude of temperature increase differs from study to study.” Table 4 - (Eriyagama et al.,2010)

Table 4 – Future Projection Studies for Sri Lanka - (Source – Eriyagama et al.,2010)

Source	Model	Scenario	Base year	Change at end of the twenty-first century (unless otherwise stated)
Cruz et al., 2007 IPCC 2007	AOGCM	A1FI	1961-1990	+5.44^{0}C (South Asia)
		B1	1961-1990	+2.93^{0}C (South Asia)
Kumar et al., 2006	RCM (PRECIS)	A2	1961-1990	+2.5 to +4^{0}C (Spatially across Sri Lanka)
		B2	1961-1990	+2 to +3^{0}C (Spatially across Sri Lanka)
Islam and Rehman. 2004	RCM (PRECIS)	A2	1961-1990	+2.5 to +4^{0}C (Spatially across Sri Lanka)
Basnayake et al., 2004	Statistical Downscaling of GCMs (HadCM3, CSIRO, CGM)	A1FI	1961-1990	+2 to +3^{0}C (range by three models for Sri Lanka as a whole)
		B1	1961-1990	+0.9 to +1.4^{0}C (range by three models for Sri Lanka as a whole)
		A2	1961-1990	+1.7 to +2.5^{0}C (range by three models for Sri Lanka as a whole)
De Silva. 2006b	Statistical Downscaling of GCMs (HadCM3)	A2	1961-1990	+1.6^{0}C by 2050s (Sri Lanka)
		B2	1961-1990	+1.2^{0}C by 2050s (Sri Lanka)

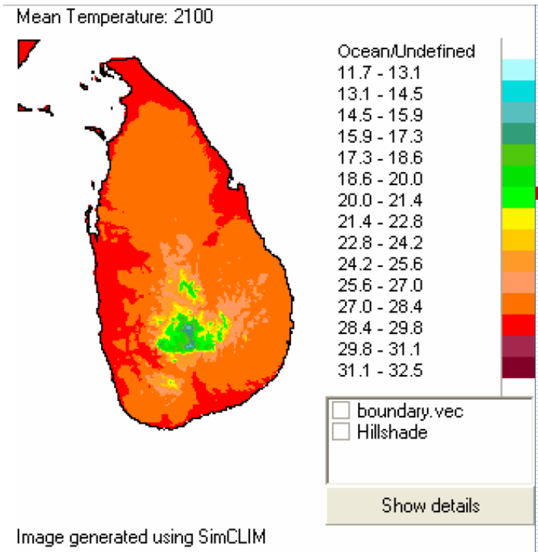


Fig. 18 - North/East Monsoon T_{mean} in 2100 (A_2). Source - (Samarasinghe, 2009)

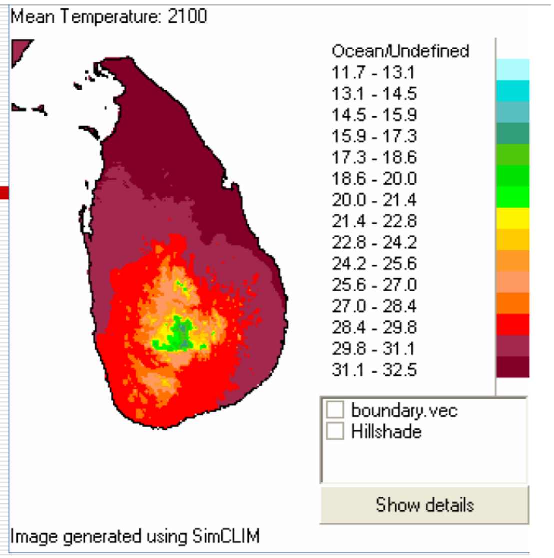


Fig. 19– South/West Monsoon T_{mean} in 2100 (A_2). Source - (Samarasinghe, 2009)

According to observed and potential impact scenarios for Sri Lanka, developed by Basnayake et al of the Department of Meteorology (Fig. 18 and Fig. 19), suggest that, under an A2 climate change scenario, Sri Lanka's Mean Temperature would rise as much as 2.4^{0}C by the year 2100. (Samarasinghe. 2009) (Table 5)

Table 5- Mean Temperature change scenario under A_2 Scenario (Annual) Source (Samarasinghe. 2009)			
Increment over the baseline			
2025	2050	2075	2100
0.4^{0}C	0.9^{0}C	1.6^{0}C	2.4^{0}C

Rainfall Projection for 2100 - Sri Lanka

According to (Eriyagama et al., 2010); "rainfall projections for Sri Lanka within this century appear to be confusing and sometimes contradictory. These projections are summarised in the form of seasonal and spatial projections in Fig. 20 for ease of understanding. The majority of models project higher Mean Annual Precipitation, but a few project lower Mean Annual Precipitation".

Rainfall projections are for both the North/East Monsoon as well as the South/West Monsoon. The overall Rainfall change is for Colombo is seen as 303 to 581mm for the North/East Monsoon and 1689 to 1967mm for the South/West monsoon. (Fig. 21 and Fig. 22)

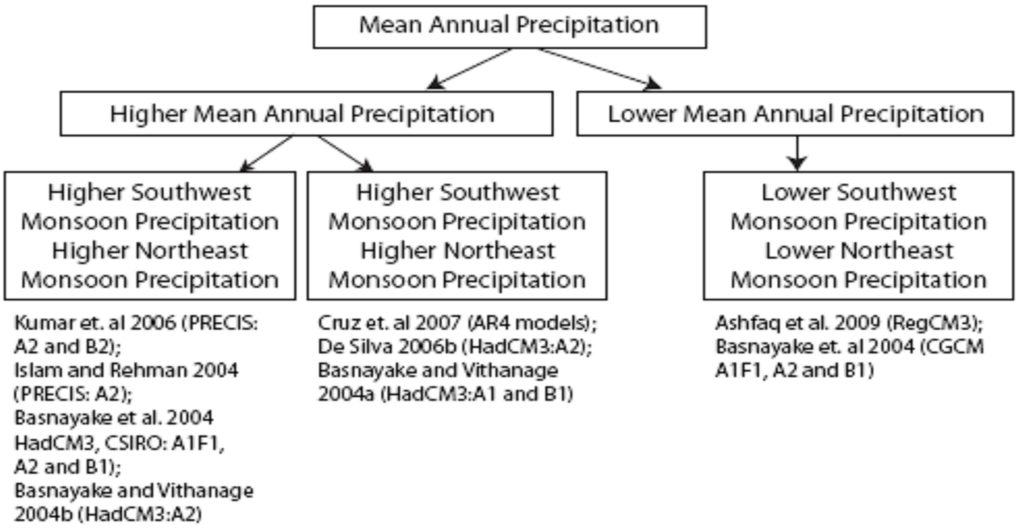
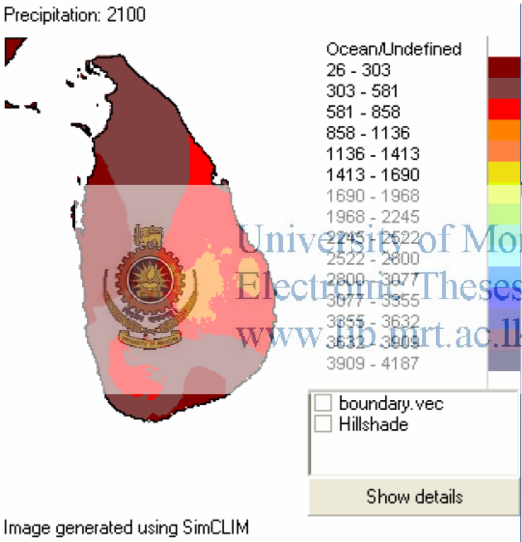


Fig. 20 - Summary of annual and seasonal rainfall projections for the 21st Century (Source – Eriyagama et al., 2010)



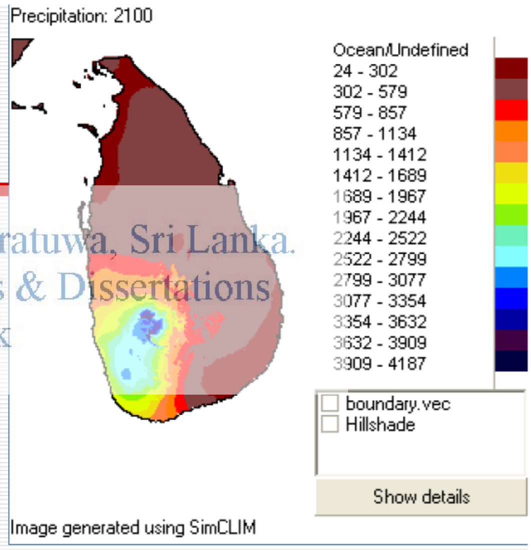


Fig. 21 - North/East Monsoon Rainfall in 2100 (A_2). Source - (Samarasinghe 2009)

Fig. 22– South/West Monsoon Rainfall in 2100 (A_2). Source - (Samarasinghe 2009)

Basnayake, 2004; forecasts that the January (Northeast monsoon) rainfall is projected to decline in the A2 scenario, while the June (Southwest monsoon) rainfall is projected to increase. (Table 6)

Table 6 - Rainfall change scenario under A_2 Scenario (Annual)

Source (Samarasinghe. 2009)

Rainfall change scenario in North/East monsoon under A2 Scenario (AR3)			Rainfall change scenario in South/West monsoon under A2 Scenario		
Increment over the baseline			Increment over the baseline		
2025	2050	2100	2025	2050	2100
25mm	54mm	143mm	175mm	402mm	1061mm

3.2 Classifying, Simplifying and Understanding the Climatic Context - for Colombo, Sri Lanka

This component of the research was published as;

Perera, N.G.R., Emmanuel, M.P.R. and Mahanama, P.K.S. (2012). Mapping Local Climate Zones and relative Warming Effects in Colombo, Sri Lanka, *proceedings of ICUC8 – 8th International Conference on Urban Climates, 6–10 August 2012, Dublin, Ireland.*

3.2.1 Classifying "Local Climate Zones"

Classification protocol

The land-use/local climate classification system defined as the Local Climate Zone (LCZ) developed by Iain Stewart uses observational data to differentiate climate zones.

The climate zone classification systems were not originally designed for mapping, it was designed to classify and standardize urban heat island observation sites, whether urban or rural, fixed or mobile. (Unger et al, 2011). Since the main objective is to simplify the urban fabric to represent a more generalised urban area, mapping is deemed a good approach to do so.

LCZs are defined as 'regions of uniform surface-air temperature distribution at horizontal scales of 10^2 to 10^4 metres' (Stewart & Oke, 2009).Their definition is based on characteristic geometry and land cover that generates a unique near-surface climate under calm, clear skies. The factors considered include vegetative fraction, building / tree height and spacing, soil moisture and anthropogenic heat flux.

LCZ has 17 climate zones as shown in Fig. 23. The zones defined as building and land cover types are combined to create sub categories. These have been validated in Sweden, Japan and Canada (Stewart, 2011) (Appendix B - LCZ datasheets)

The sequential process adopted is based on the guidelines for classifying heat island field sites into local climate zones developed by Iain Stewart (2011)

Step 1 – Define the area of influence

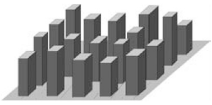
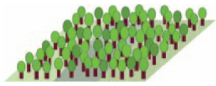
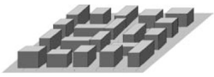
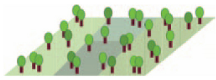
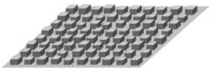
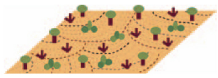
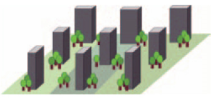
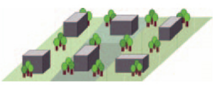
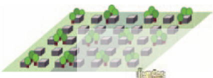
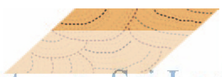
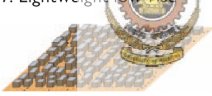
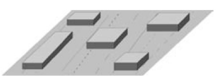
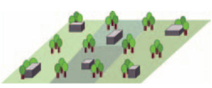
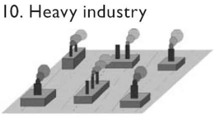
Built types	Definition	Land cover types	Definition
1. Compact high-rise 	Dense mix of tall buildings to tens of stories. Few or no trees. Land cover mostly paved. Concrete, steel, stone, and glass construction materials.	A. Dense trees 	Heavily wooded landscape of deciduous and/or evergreen trees. Land cover mostly pervious (low plants). Zone function is natural forest, tree cultivation, or urban park.
2. Compact midrise 	Dense mix of midrise buildings (3–9 stories). Few or no trees. Land cover mostly paved. Stone, brick, tile, and concrete construction materials.	B. Scattered trees 	Lightly wooded landscape of deciduous and/or evergreen trees. Land cover mostly pervious (low plants). Zone function is natural forest, tree cultivation, or urban park.
3. Compact low-rise 	Dense mix of low-rise buildings (1–3 stories). Few or no trees. Land cover mostly paved. Stone, brick, tile, and concrete construction materials.	C. Bush, scrub 	Open arrangement of bushes, shrubs, and short, woody trees. Land cover mostly pervious (bare soil or sand). Zone function is natural scrubland or agriculture.
4. Open high-rise 	Open arrangement of tall buildings to tens of stories. Abundance of pervious land cover (low plants, scattered trees). Concrete, steel, stone, and glass construction materials.	D. Low plants 	Featureless landscape of grass or herbaceous plants/crops. Few or no trees. Zone function is natural grassland, agriculture, or urban park.
5. Open midrise 	Open arrangement of midrise buildings (3–9 stories). Abundance of pervious land cover (low plants, scattered trees). Concrete, steel, stone, and glass construction materials.	E. Bare rock or paved 	Featureless landscape of rock or paved cover. Few or no trees or plants. Zone function is natural desert (rock) or urban transportation.
6. Open low-rise 	Open arrangement of low-rise buildings (1–3 stories). Abundance of pervious land cover (low plants, scattered trees). Wood, brick, stone, tile, and concrete construction materials.	F. Bare soil or sand 	Featureless landscape of soil or sand cover. Few or no trees or plants. Zone function is natural desert or agriculture.
7. Lightweight low-rise 	Dense mix of single-story buildings. Few or no trees. Land cover mostly hard-packed. Lightweight construction materials (e.g., wood, thatch, corrugated metal).	G. Water	Large, open water bodies such as seas and lakes, or small bodies such as rivers, reservoirs, and lagoons.
8. Large low-rise 	Open arrangement of large low-rise buildings (1–3 stories). Few or no trees. Land cover mostly paved. Steel, concrete, metal, and stone construction materials.	**VARIABLE LAND COVER PROPERTIES**	Variable or ephemeral land cover properties that change significantly with synoptic weather patterns, agricultural practices, and/or seasonal cycles.
9. Sparsely built 	Sparse arrangement of small or medium-sized buildings in a natural setting. Abundance of pervious land cover (low plants, scattered trees).	*b. bare trees*	Leafless deciduous trees (e.g., winter). Increased sky view factor. Reduced albedo.
		s. snow cover	Snow cover >10 cm in depth. Low admittance. High albedo.
10. Heavy industry 	Low-rise and midrise industrial structures (towers, tanks, stacks). Few or no trees. Land cover mostly paved or hard-packed. Metal, steel, and concrete construction materials.	*d. dry ground*	Parched soil. Low admittance. Large Bowen ratio. Increased albedo.
		w. wet ground	Waterlogged soil. High admittance. Small Bowen ratio. Reduced albedo.

Fig. 23 - Definitions for Local Climate Zones (Source - Stewart & Oke, 2012)

In Ian Stewart's outline for field site selection is based on measurement conditions influencing the station set up in an urban context to be studied. These encompass; height above ground, building morphology, tree density, boundary layer stability, period of observation and wind direction.

Quantification of transitional urban–rural areas or along breaks in land-use and filed sites or source areas located on or near the border of two (or more) zones is problematic. The ideal situation would be to relocate the sensor to encompass a single LCZ type. Land cover and exposure at that location should be representative of the designated LCZ: for compact built zones (e.g. LCZs 1–3), 'representative' implies a sheltered street canyon with paved ground; for open built zones (e.g. LCZs 4–6), it implies an exposed setting with vegetated ground, scattered trees, and nearby buildings. (Stewart and Oke, 2012).

The approach here is to understand the city in terms morphology and its influence. Therefore, the 'area of influence' selection, adopts 'urban blocks' as the primary defining element for the study.

The selection of an urban block as a particular defined element allows effective simulation in the envisioned - next steps - in the research. The urban block offers a definite boundary, be it street, a green area or water body. Factors encompassing geometric and surface cover characteristics are better defined and easily quantifiable in a situation where the boundaries and area are well established.

The primary advantage is for mapping purposes, where LCZs are identified as more recognizable regions in the urban fabric. Therefore, offers better applicability for planning and urban design.

The approach is now widely adopted for mapping studies. The most prominent being the WUDAPT protocol, outlined in Chapter 2. The primarily elements for creating 'training sites' - for establishing input parameters for the remote sensed component - are urban blocks. The remote sensed classification then uses a grids to simplify and classify the urban context.

The research primarily uses a detailed map of Colombo (in Autodesk AutoCAD format generated from Geographic information system (GIS) data for Colombo, 2010) to establish the urban blocks for LCZ definition. The map includes urban blocks and building outlines, roads, water bodies and land Contours. (Fig. 24). The verification and modification of the block boundaries was done using on-field surveys and Google Earth Imagery.

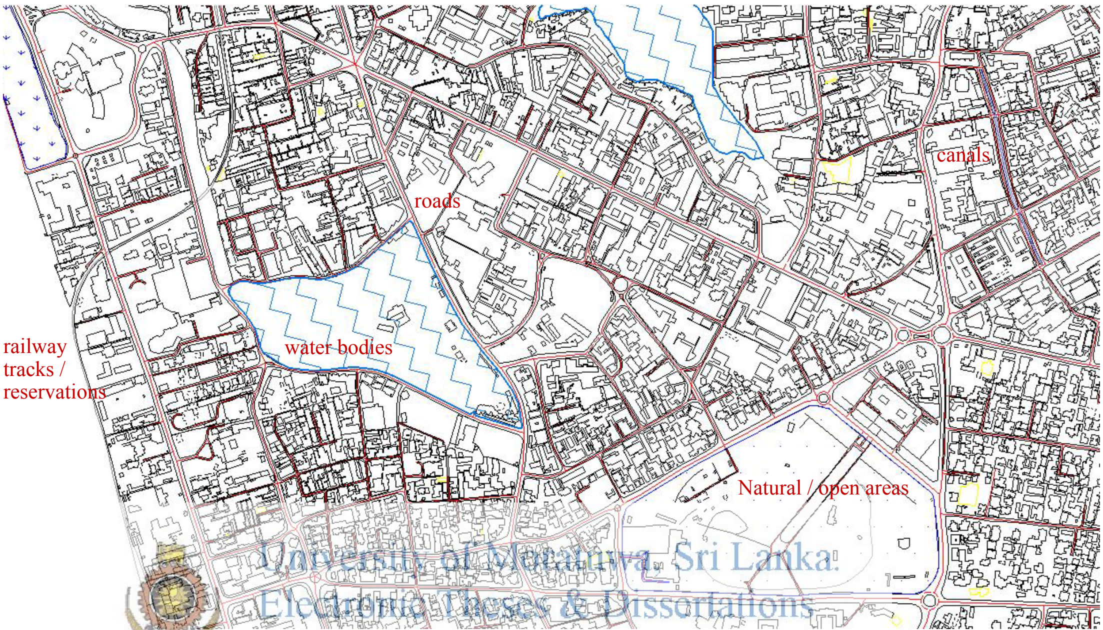


Fig. 24 - Representative sample area of the Detailed map of Colombo - demonstrating the typical urban block boundaries. (Source - Author)

Step 2 – Collect site metadata

Metadata refers to the state of the urban context around a particular measurement site. The recording the surrounding of a measurement site ensures the consideration of the effect of the existing built fabric in relation to future changes on a particular site, measured at a future date. The protocol to be adopted is defined by Oke (2004) and Aguilar et al, (2003).

In this situation, the objective is to establish and simplify the nature of the urban fabric itself. The data collected adhered to the 'Zone Properties' defined in the 'Local Climate Zone' Data sheets developed by Stewart, 2011 [Appendix B & 3.3(a & b)] Outlined in Table 7; are the methods adopted to observe each property.

Table 7 - Urban block meta data and data collection methods

Property	Definition	Method adopted
Sky View Factor (SVF)	Ratio of the amount of sky hemisphere visible from ground level to that of an unobstructed hemisphere	Fish-eye Lens Photographs, Field surveys
Aspect ratio (H/W)	Mean height-to-width ratio of street canyons (LCZs 1–7), building spacing (LCZs 8–10), and tree spacing (LCZs A–G)	Detailed maps, Field surveys, Google earth
Building Surface fraction (BSF)	Ratio of building plan area to total plan area (%)	Detailed maps, Google earth, Field surveys
Impervious Surface fraction (ISF)	Ratio of impervious plan area (paved, rock) to total plan area (%)	Detailed maps, Google earth, Field surveys
Pervious surface fraction (PSF)	Ratio of pervious plan area (bare soil, vegetation, water) to total plan area (%)	Detailed maps, Google earth, Field surveys
Height of Roughness Elements (HRE)	Geometric average of building heights (LCZs 1–10) and tree/plant heights (LCZs A–F) (m)	Detailed maps, Field surveys, Google earth
Terrain Roughness class	Davenport et al.,'s (2000) classification of effective terrain roughness (z0) for city and country landscapes	As per LCZ data sheets
Surface admittance	Ability of surface to accept or release heat (J m–2 s–1/2 K–1). Varies with soil wetness and material density. Few estimates of local-scale admittance exist in the literature; values given here are therefore subjective and should be used cautiously. Note that the "surface" in LCZ A is undefined and its admittance unknown.	LCZ data sheet as guide
Albedo	Ratio of the amount of solar radiation reflected by a surface to the amount received by it. Varies with surface color, wetness, and roughness.	LCZ data sheets based on field survey observations
Anthropogenic heat flux	Mean annual heat flux density (W m^{-2}) from fuel combustion and human activity (transportation, space cooling/heating, industrial processing, and human metabolism). Varies significantly with latitude, season, and population density	As per LCZ data sheets

Step 3 – Select LCZ

The relevant Local Climate Zone for each block is selected by correlating the observed data with that of the selection guideline developed by Stewart, (2011).

The guidelines are broadly categorised according to (Fig. 23 and Appendix B);

- Zone definition - Physical characteristics that all zones in this class possess
- Zone illustration – Typical views of the built fabric portrayed using sketches and images
- Zone properties – Parameters that are deemed to drive the Urban Heat Island phenomenon.

Step 3b – Sub-classify Zone

The selected LCZ category for each urban block is then sub-classified, by combining LCZ classes where necessary. (Fig. 25) The sub-classification depends on how the site properties differ from the nearest equivalent in the data set. As defined, consideration is given to building types, special building properties, land cover types and seasonal land cover properties.

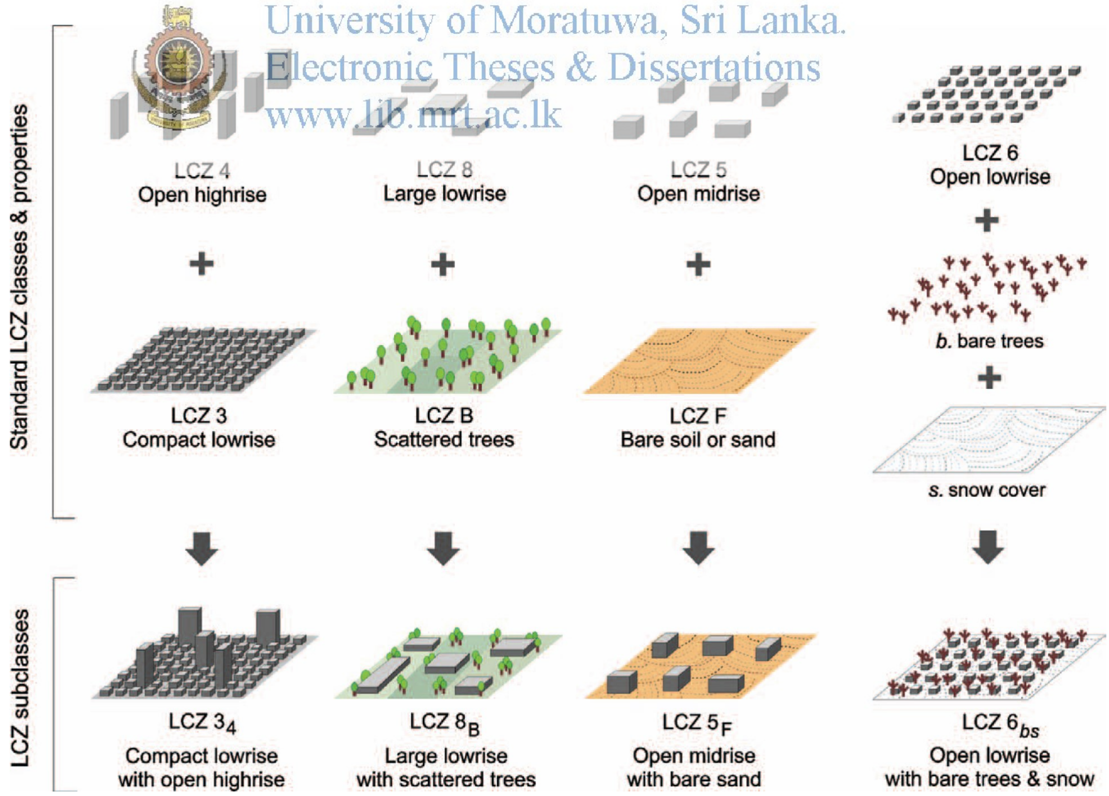


Fig. 25 – LCZ subclasses to represent combinations of "built" and "land cover" types.
(Source – Stewart and Oke, 2012)

3.2.2 - Classifying "Local warming effects" of the urban fabric

Likely local warming effects of the urban fabric classified according to LCZs are simulated using the Surface Heat Island Model (SHIM) developed by Johnson et al., (1991). The SHIM is a simple force-restore model that simulates the nocturnal cooling of an urban canyon (walls and street) under 'ideal' conditions of calm winds and clear skies. SHIM is initiated at the time of sunset and requires several inputs to run the model. These include initial surface temperatures, emissivities, thermal admittance, and deep temperatures for each canyon facet, incident long-wave radiation (L↓) at the top of the canyon and the canyon height to width ratio (H/W). The model is set up to calculate surface cooling for each of the canyon facets and also calculates the surface radiation budget (L*) for each of the facets (Szpirglas et al, 2003) (Fig. 26)

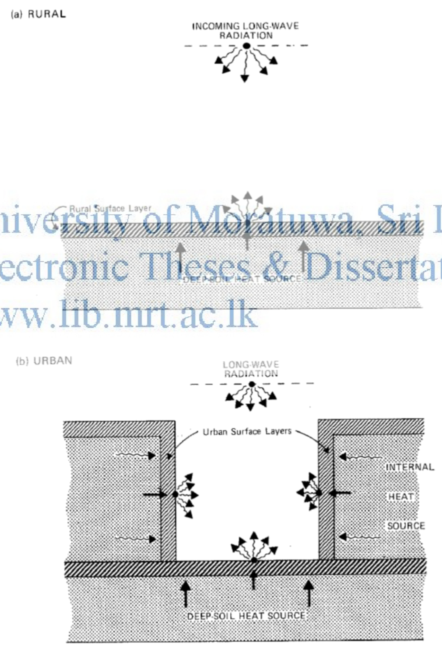


Fig. 26 – Rural / Urban surfaces
(Source – Johnson et al., 1991)

As seen in Fig. 26, the model is based on a two-layer approximation of soil temperature changes (a small top surface soil layer that responds to near-periodic daily forcing and a deep soil layer underneath that does not respond to periodic forcing). The surface forcing is due to radiative changes during the day as well as the restoration by the deep soil layer from below. This forcing is 'idealised' thus, no possibility exists to account for variable cloud cover or frontal conditions. A detailed view of the model and its validation can be found in (Szpirglas & Voogt, 2003) and (Brazel & Crewe, 2002)

Szpirglas and Voogt assessed the model performance under varying weather conditions. It was found that "There was a close agreement between observed and modelled temperatures for days with clear skies and light winds. The agreement declined with an increase in wind speed, as high wind speeds caused rapid cooling in the observed surface temperatures. The results suggest that SHIM may be usefully applied under wind conditions of <1.5 m s-1 in its present formulation". (Szpirglas & Voogt, 2003) The validation of the model showed that days that included scattered clouds resulted in poor model performance.

Turbulence and advection are not incorporated. It is assumed that all cooling takes place due radiative heat loss. No account of evaporative heat transfer is possible. However, the SHIM is an excellent tool to isolate the effects of urban geometries (density, height: width ratio and the sky view factor) as well as surface thermal properties. It thus enables us to explore the urban warming potential of rapid changes in urban growth epitomised by densely arranged buildings with excessive thermal capacities. (Emmanuel et al., 2011)

The governing force-restore equation used by SHIM for the nocturnal cooling of a homogeneous substrate with layer thickness D is given as:

$$\frac{dT\ (D_i, t)}{dt} = \frac{\sqrt{2\Omega}}{\mu_i} L^*{}_i - \Omega(T_i(D_i, t) - T_D)$$

Where T(D*i*,t) is the temperature of a layer *i* at time t, TD represents a "deep temperature" that is constant, μ is the thermal admittance of the soil, Ω is the angular frequency of the heating wave and L* is the net long-wave radiation

SHIM requires initial values of the surface temperature (T), deep soil and/or building temperature (TG or TB), surface thermal admittance (μ), sky view-factor (ψs) and surface emissivity (ε) for all of the surfaces to be simulated in addition to the incoming long-wave radiation to the total system (L↓).

Values for each were determined by various means as outlined below together with the values defined by the individual LCZs. These measured values were also used as metadata for the classification of LCZs.

- T Measured directly or a measured near-surface air temperature was used as a surrogate, (using Technotherm 9400 Surface Temperature Probe)
- T_G using synoptic weather station data.
- T_B Estimated from building interior set point temperature (assumed to be 27°C)
- μ Estimated from published values (e.g. Oke, 1987)
- Ψ_s Calculated from fisheye lens photographs
- ε Estimated from published values (especially Arnfield, 1982 and Oke, 1987)
- $L\downarrow$ Calculated using the empirical formulae of Idso and Jackson (1969) (with measured humidity and air temperature, (30 year average data recorded at the weather stations stated below). $L_0/s\ T^4 = 1 - 0.261 \exp[-0.000777(273 - T)^2]$ (deemed applicable for all latitudes and seasons)

The numerical model was run in a Microsoft Excel environment based on data measured on a stable day (January 04, 2011) in Colombo, Sri Lanka. The SHIM model simulation results are compared with the rate of cooling at a 'rural' station (using data from the synoptic weather station at the Colombo International Airport (Lat: 7° 10'N; Lon: 79° 52'E; Elevation: 8m asl; WMO Station ID: 434500) and an 'urban' weather station at the Colombo City Airport (Lat: 6° 49'N; Lon: 79° 52'E; Elevation: 5m asl; WMO Station ID: 434670).(Appendix D)

3.2.3 Detailed categorisation of the mapped local level urban climate characteristics effecting Colombo

The detailed categorisation utilises the application of the two processes detailed above in Section 3.2.1 and 3.2.2. The results and discussion of the sequential processes presented below.

<u>Mapping "Local Climate Zones" - results and discussion</u>

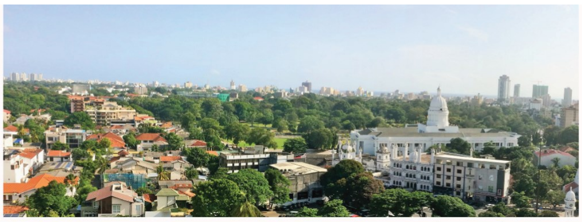
The relevant LCZ for each block is selected by correlating the observed data with that of the selection guideline developed by Stewart *et al*., (2012)

The survey of LCZ typologies relevant for Colombo showed that much like many cities in developing countries Colombo is dominated by residential and mixed-use zones. Although large areas of Colombo remain low rise, these urban blocks are seeing an infusion of mid-rise and high-rise blocks. Fig. 27 demonstrates representative images of typical LCZs in Colombo. Most of the zones classify as LCZ3 – Compact Low-rise (48.1%), LCZ2 – Compact Midrise (8.9%) and LCZ8- Large Low-rise (23.7%) categories. LCZ1 – Compact High-rise (0.3%) and LCZ4 – Open High-rise (1%) form a very small fraction of Colombo's built fabric. A significant percentage falls under the category LCZ7- Lightweight Low-rise (4.9%). (Fig. 28 and Fig. 29)(Table 8)

Table 8 - LCZ and Sub-Classification Patterns for Colombo

LOCAL CLIMATE ZONE		**Sub-Classification Category**														
Zone Number	**Zone Title**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**A**	**B**	**C**	**D**	**E**	**F**	**G**
1	compact high-rise	x														
2	compact mid-rise		x	x	x			x								
3	compact low-rise		x	x	x	x	x	x								
4	open high-rise		x	x	x								x			
5	open mid-rise			x	x	x					x		x	x	x	
6	open low-rise			x		x	x	x		x	x		x		x	
7	lightweight low-rise			x				x								
8	large low-rise		x	x	x	x		x	x		x		x	x	x	
A	dense trees									x						
B	scattered trees										x					
C	bush, scrub															
D	low plants												x			
E	bare rock or paved													x		
F	bare soil or sand														x	
G	water															x

LCZ1, LCZ 8. (Source: Dissanayake, 2015)



LCZ3, LCZ2, LCZ8, LCZB. (Source: Dissanayake, 2015)

LCZ1, LCZ3. (Source: Dissanayake, 2015

LCZ2. Source: Dissanayake, 2015)

LCZ D, LCZ8. (Source: Dissanayake, 2015)

LCZ3. (Source: Dissanayake, 2015)

LCZ G, LCZ8, LCZ7. (Source: Muthugala, 2011)

LCZ data key denotes: 1 – compact high-rise; 2 – compact mid-rise; 3 – compact low-rise; 4 –open high-rise; 5 – open mid -rise; 6 – open low-rise; 7 – lightweight low-rise; 8 – large low-rise; A – dense trees; B – scattered trees; C – bush, scrub; D – low plants; E – bare rock or paved; F – bare soil or sand; G – water.

Fig. 27 - Typical LCZs of Colombo - representative images

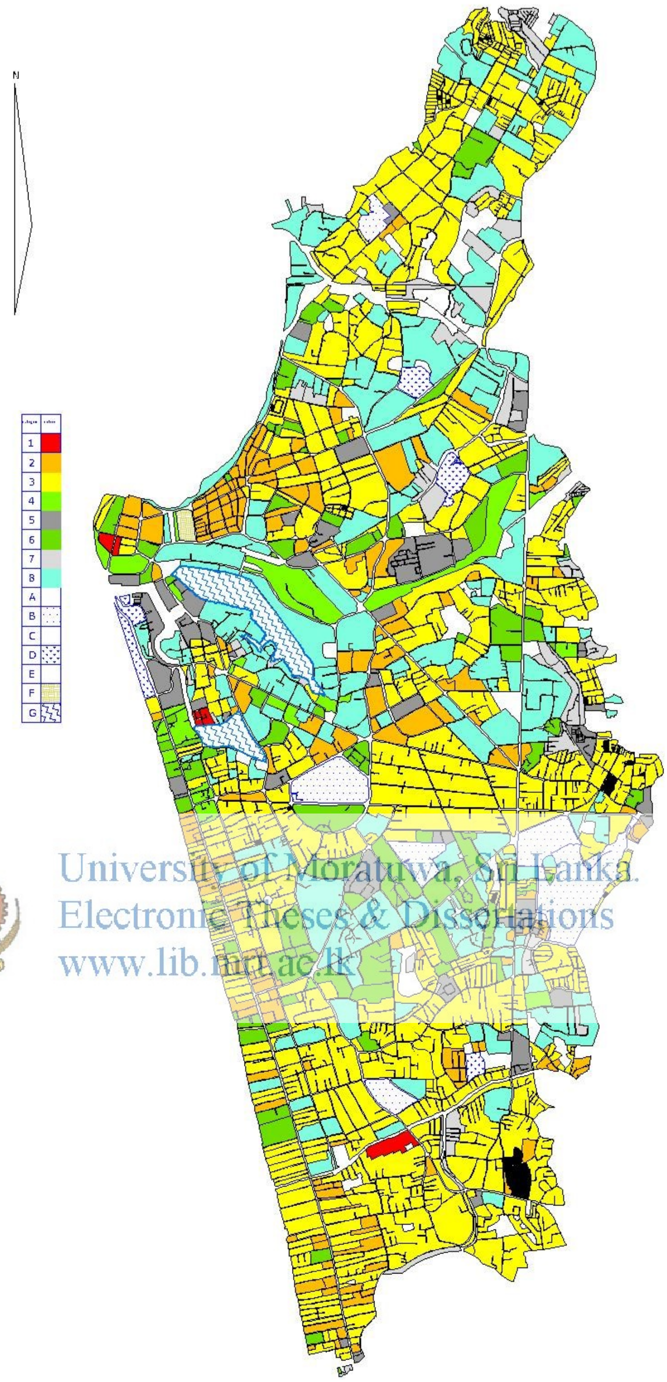


Fig. 28 - LCZ map of Colombo.

LCZ data key denotes -1- Compact Highrise,2 – Compact Midrise, 3 – Compact Low-rise, 4-Open High-rise, 5-Open Midrise, 6-Open Low-rise, 7-Lightweight Low-rise, 8-Large Low-rise, A-dense trees, B-Scattered Trees, C-Bush, Scrub, D-Low Plants, E-Bare Rock or Paved, F-Bare Soil or Sand, G-Water

The process of sub-classification of the primary LCZs is seen as an important step in relation to cities like Colombo, which has grown with time as opposed to being a planned city. A significant proportion of the LCZs needed to be sub-classified to project a better representation of its characteristics. (Fig. 29)

The sub-classification of the compact fabric series sees a sub-classification with LCZs of mainly the building series. While the open fabric series is sub-classified with LCZs of the land-cover series. This is most evident in LCZ8, where the nature of the open ground is significant.

LCZ3 with sub-classification LCZ7 is noteworthy, where these areas would have been previously categorised as Lightweight Low-rise or shanty areas in the city, has now developed with more permanent materials. The development has not changed its plot structure; therefore maintain a high aspect ratio.

Surface Heat Island Model (SHIM) Application

Table 9, details the input values for each Surface Heat Island Model (SHIM) calculation. The values follow the data sources outlined in Section 3.2.2 in this chapter. Typical Microsoft Excel based input screen shown in Appendix E. The numerical simulation demonstrates input value format, output data and graphs signifying the cooling of the canyon surface.

The categorisation is presented in the form of a matrix of LCZs modified by the morphology, surface characteristics of the urban fabric and the local level warming intensity ascertained by the SHIM models as shown in Table 10.

The categorisations and sub-categorisations in Table 10 and the key in Fig. 28 and Fig. 29, refer to the nomenclature as defined in Fig. 23. The shaded diagonal depicts LCZs that are not sub-categorised. The y-axis shows the primary categorisation of LCZs, while the x-axis shows the sub-categorisation LCZs. The values depicted in the intersects detail the UHI intensity difference between the LCZ and the representative / control 'rural' LCZ.

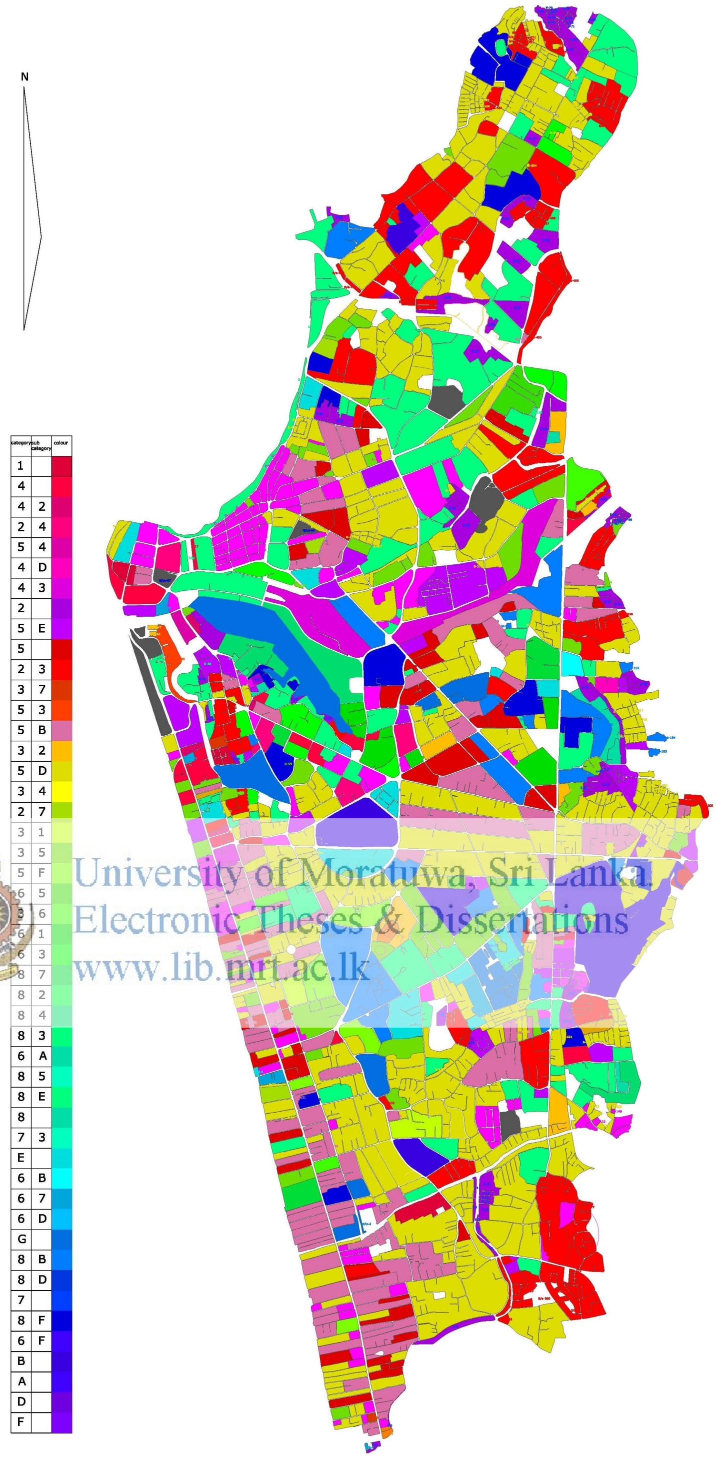


Fig. 29 - Sub-Classified LCZ map of Colombo. (Source - author)
LCZ data key denotes -1- Compact Highrise,2 – Compact Midrise, 3 – Compact Low-rise, 4-Open High-rise, 5-Open Midrise, 6-Open Low-rise, 7-Lightweight Low-rise, 8-Large Low-rise, A-dense trees, B-Scattered Trees, C-Bush, Scrub, D-Low Plants, E-Bare Rock or Paved, F-Bare Soil or Sand, G-Water

Table 9 - Input data for Surface Heat Island Models (as defined in section 3.2.2) (Source - Author.)

category	sub-category	floor emissivity	wall emissivity	floor admittance	wall admittance	H/W	Tw1	Tw2	Urban temperature dif	Rural temp dif	temp diff u-r
1		0.95	0.895	1205	2200	6	35.5	38.2	0.84	5.24	4.40
2	3	0.85	0.91	1524	2000	2	34.3	35.5	1.68	5.24	3.56
2	4	0.85	0.91	1524	2000	3.5	34.3	38.2	1.10	5.24	4.15
2	7	0.9	0.85	1524	1900	1.5	34.3	35.5	2.03	5.24	3.22
2		0.85	0.91	1524	2000	3	34.3	35.5	1.28	5.24	3.96
3	2	0.85	0.91	1700	2000	1.5	34.3	35.5	1.92	5.24	3.33
3	4	0.95	0.91	1700	2200	1.6	34.3	35.5	1.94	5.24	3.30
3	5	0.95	0.91	1700	2000	1.4	34.3	35.5	2.11	5.24	3.13
3	6	0.95	0.91	1700	2000	0.75	34.3	35.5	2.99	5.24	2.26
3	7	0.96	0.8	1600	1800	2	34.3	35.5	1.74	5.24	3.50
3		0.85	0.91	1754	2000	1.3	34.3	35.5	2.06	5.24	3.19
4	2	0.93	0.895	1600	2100	3.5	35.5	34.3	1.09	5.24	4.16
4	3	0.93	0.895	1575	2000	3	35.5	34.3	1.22	5.24	4.02
4	D	0.93	0.895	950	2200	4.5	35.5	38.2	1.12	5.24	4.12
4		0.93	0.895	1675	2200	4.5	35.5	38.2	0.89	5.24	4.35
5	3	0.93	0.91	1524	2000	2	34.3	34.3	1.78	5.24	3.47
5	4	0.85	0.91	1700	2000	3.5	34.3	35.5	1.11	5.24	4.14
5	B	0.96	0.91	1090	2000	2.5	34.3	34.3	1.81	5.24	3.43
5	D	0.97	0.91	950	2000	2.5	34.3	34.3	1.93	5.24	3.31
5	E	0.94	0.91	1719	2000	2.5	34.3	34.3	1.45	5.24	3.79
5	F	0.95	0.91	700	2000	2.5	34.3	34.3	2.17	5.24	3.07
5		0.93	0.91	1524	2000	2.5	34.3	34.3	1.53	5.24	3.71
6	3	0.93	0.91	1600	2000	0.5	34.3	34.3	3.61	5.24	1.63
6	5	0.93	0.91	1700	2000	0.75	34.3	35.5	2.95	5.24	2.29
6	7	0.95	0.8	1500	1800	0.3	34.3	34.3	4.35	5.24	0.89
6	A	0.97	0.91	1200	2000	0.6	34.3	34.3	4.03	5.24	1.21
6	B	0.96	0.91	1090	2000	0.6	34.3	34.3	4.21	5.24	1.03
6	D	0.93	0.91	950	2000	0.6	34.3	34.3	4.44	5.24	0.80
6	F	0.95	0.91	700	2000	0.6	34.3	34.3	5.16	5.24	0.09
6		0.93	0.91	1597	2000	0.6	34.3	35.5	3.37	5.24	1.87
7	3	0.9	0.35	1448	600	4	32.1	34.3	4.21	5.24	1.04
7		0.85	0.205	1448	400	3	32.1	38.2	4.93	5.24	0.31
8	2	0.95	0.45	1700	1000	0.5	34.3	38.2	3.77	5.24	1.48
8	3	0.95	0.45	1700	1000	0.4	34.3	38.2	3.96	5.24	1.29
8	4	0.95	0.7	1700	1200	0.4	34.3	38.2	3.87	5.24	1.37
8	5	0.95	0.45	1700	1000	0.35	34.3	38.2	4.05	5.24	1.19
8	7	0.93	0.45	1600	1000	0.6	34.3	38.2	3.68	5.24	1.56
8	B	0.96	0.45	1090	1000	0.3	34.3	38.2	4.67	5.24	0.57
8	D	0.93	0.45	950	1000	0.3	34.3	38.2	4.73	5.24	0.52
8	E	0.94	0.45	1719	1000	0.3	34.3	38.2	4.09	5.24	1.15
8	F	0.95	0.45	700	1000	0.3	34.3	38.2	5.04	5.24	0.20
8		0.95	0.45	1700	1000	0.3	34.3	38.2	4.14	5.24	1.10
A		0.97		1182					5.36	5.24	-0.12
B		0.96		1182					5.33	5.24	-0.09
C										5.24	5.24
D		0.93		938					5.89	5.24	-0.64
E		0.91		1719					4.21	5.24	1.04
F		0.76		700					6.14	5.24	-0.90
G		0.97		1553					4.63	5.24	0.62

Table 10 - Urban – Rural Temperature Difference

LOCAL CLIMATE ZONE	LOCAL CLIMATE ZONE (LCZ)– Sub Category														
	1	2	3	4	5	6	7	8	A	B	C	D	E	F	G
1	4.40														
2		3.96	3.56	4.15			3.22								
3		3.33	3.19	3.30	3.13	2.26	3.50								
4		4.16	4.02	4.35								4.12			
5			3.47	4.14	3.71					3.43		3.31	3.79	3.07	
6			1.63		2.29	1.87	0.89		1.21	1.03		0.80		0.09	
7			1.04				0.31								
8		1.48	1.29	1.37	1.19		1.56	1.10		0.57		0.52	1.15	0.20	
A									-0.12						
B										-0.09					
C															
D												-0.64			
E													1.04		
F														-0.90	
G															0.62

3.2.4 Analysis and discussion - establishing the focus for further study.

The basis for analysis is centred on the matrix (Table 10) developed by LCZ mapping and application of SHIM presented in the preceding sections. The objective of the analysis is to establish a focus on the critical patterns to create effective limitations to the research.

Discussion

Significant urban warming can be seen at sites with high-rise developments and also where they are present within other LCZs as a sub-category. Although in Colombo these sites are few and far between amounting to only 0.3% of the built areas considered. (Table 10)

Areas with the largest intensity of urban growth, LCZ3 - Compact Low-rise and LCZ2 – Compact Mid-rise are greatly affected by the mixing of the built fabric with a range of 1.5^{o}C difference in UHI intensity between the categorised typologies.

The lowest intensity is seen from the Land Cover type LCZs. The land cover sub-categorisation becomes significant in LCZ8 – Large Low-rise and LCZ6 - Open Low-rise, where LCZ8 areas form a large part of the city, mainly along the cities canal system.

The areas with the highest built area fraction, LCZ7 – Lightweight Low-rise areas are affected significantly by the material properties modelled. (Thermal admittance and Emissivity). Significant areas of the city have seen previously LCZ7 areas develop into LCZ3, while maintaining the built surface fraction and H/W ratios. LCZ7 areas have a UHI Intensity of only 0.3°C, while LCZ3 areas with a LCZ7 sub category have a greater intensity of 3.5°C. (Perera et al., 2012)

LCZ Analysis – Critical Local Climate Zone Selection

Analysis of Zone classification to the UHI intensity is further explored by using a simple scatter plot that compares the local warming differences of each LCZ category. (Fig. 30)

The graph (Fig. 30) clearly demonstrates the critical LCZ categories are from LCZ1 - Compact High-rise to LCZ5 – Open Mid-rise. LCZ1– Compact High-rise and LCZ4-Open High-rise, though greatly affected by UHI form a small part of Colombo's urban fabric. Yet, with the rapid development of Colombo these LCZs deserve consideration. In Colombo's context, LCZ5 is a variation of the built area fraction of LCZ2 and thus will be addressed in the simulations encompassing LCZ2.

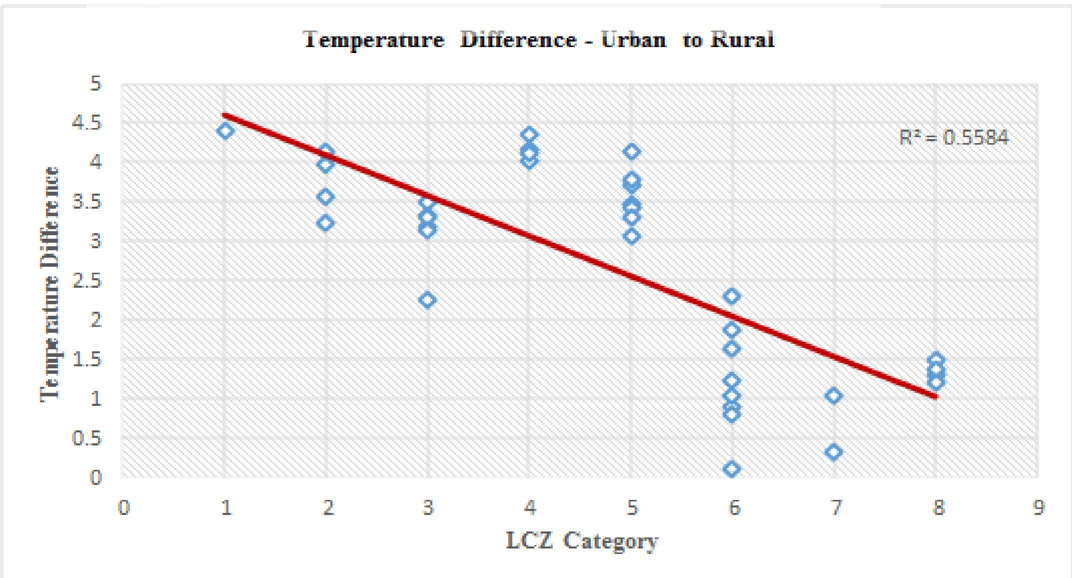


Fig. 30 – Analysis of zone classification and UHI intensity (Source - Author)

In consideration of the above, it is deemed that LCZ2 – Compact Mid-rise and LCZ3 – Compact Low-rise are significant in terms of both UHI intensity and the area they occupy in Colombo's urban fabric. Therefore, they can be identified as critical patterns that need to be concentrated upon.

The research direction being primarily focussed on morphology, the LCZ patterns are narrowed to a range between encompassing LCZ2 and LCZ3. LCZ5 is excluded as it is considered as a change in the building spacing in comparison to LCZ2, rather than a morphology change. It is envisioned that the Built to open surface fraction will be explored in developing simulation cases within the selected LCZs in the next stages of the research.

3.3 Computer Simulation of climatic contexts, existing and modified building morphology and using ENVI-met

Analysis and discussion of existing and projected urban growth areas highlighted as critical in the LCZ mapping, is based on computer simulations using ENVI-met. The simulations involve a series of urban fabric options to enhance the adaptive possibilities of changes within the critical LCZ2 pattern. Analysis outlines what works and how sensitive are urban morphological factors in controlling / adapting to local warming.

3.3.1 ENVI-met - the model, Input variables, output possibilities, Limitations and validation

ENVI-met, the holistic microclimate modelling system. ENVI-met is a three-dimensional microclimate model designed to simulate the surface-plant-air interactions in urban environment with a typical resolution down to 0.5 m in space and 1- 5 sec in time. (envi-met.info). (Fig. 31)

Ali-Toudert & Mayer, 2006 state:

> The major advantage of ENVI-met is that it is one of the first models that seeks to reproduce the major processes in the atmosphere that affect the

microclimate, including the simulation of wind flows, turbulence, radiation fluxes, temperature and humidity, on a well-founded physical basis (i.e. the fundamental laws of fluid dynamics and thermodynamics). ENVI-met simulates the microclimatic dynamics within a daily cycle in complex urban structures, i.e. buildings with various shapes and heights as well as vegetation. Its high spatial and temporal resolution enables a fine understanding of the microclimate at street level. It also requires relatively few input parameters, and calculates all important meteorological factors, e.g. air and surface temperatures, wind speed and direction, air humidity, short-wave and long-wave radiation fluxes, as well as the mean radiant temperature needed for comfort analyses.

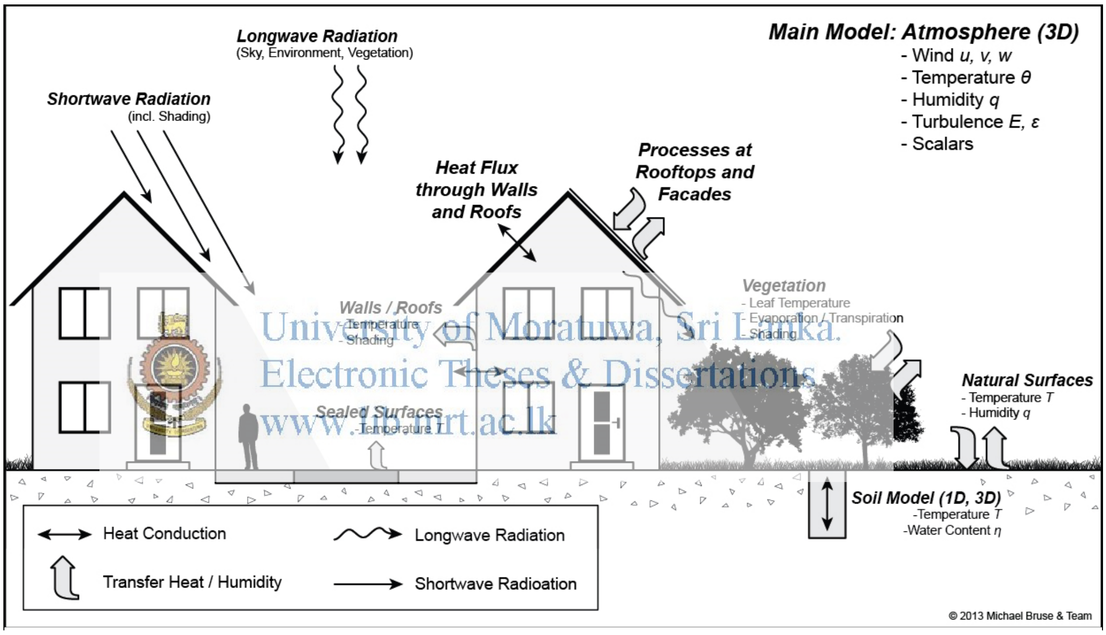


Fig. 31 – ENVI-met Overview (Source – www.ENVI-met.com)

The initial component of the simulation is the simplified model of the urban fabric morphology. It includes buildings - expressed as multiples of a standard grid, therefore plan dimensions and height, trees, man-made and natural surfaces (including water). (Appendix F)

Input data required to initiate ENVI-met simulations are expressed as two parts; basic data and optional data. Basic data encompasses;

- Wind Speed in 10 m above ground [m/s]
- Wind Direction (0:N..90:E..180:S..270:W..)

- Roughness Length z0 at Reference Point
- Initial Temperature Atmosphere [K]
- Specific Humidity in 2500 m [g Water/kg air]
- Relative Humidity in 2m [%]

Optional data are input as parameters that define the nature of; Soil Data; Time (simulation time and time steps); Building properties (U-values, Albedo, Internal Temperature); Predicted Mean Vote (clothing, activity etc.); Cloud data; Turbulence. (Appendix G)

The model includes the simulation of:

- Flow around and between buildings
- Exchange processes at the ground surface and at building walls
- Building physics
- Impact of vegetation of the local microclimate
- Bioclimatology
- Pollutant dispersion

(envi-met.info)

The main limitations of the software are seen in the simplification of the urban fabric into uniform modules of a certain size. The modules take the form of 'grids', therefore building foot prints and vertical scaling are multiples of the chosen grid, limiting the representation of the heterogeneous nature of the city fabric. Similarly, "the properties (such as albedo and U-value) are applied equally to all walls and roofs respectively. Further, the heat storage term for the buildings, which calculates the time lag, is not included in the energy balance of the building surfaces. Due to this fact, the thermal mass of vertical constructions, which causes delayed heat dissipation, is not taken into account for buildings, as it is for ground paving and soils." (Spangenberg et al, 2008)

ENVI-met - validation

ENVI-met was validated for Sri Lanka by Emmanuel & Fernando, 2007. Fig. 32 compares the ENVI-met simulations to actual measured data for Pettah, Colombo. The model tends to over-predict the air temperature at night (average absolute difference during 19:00 to 05:00 h = 0.27°C; root mean square error RMSE = 1.06° C) and under-predicts during the day (average absolute difference during 07:00 to 17:00 h = 1.83°C; RMSE = 2.73°C).

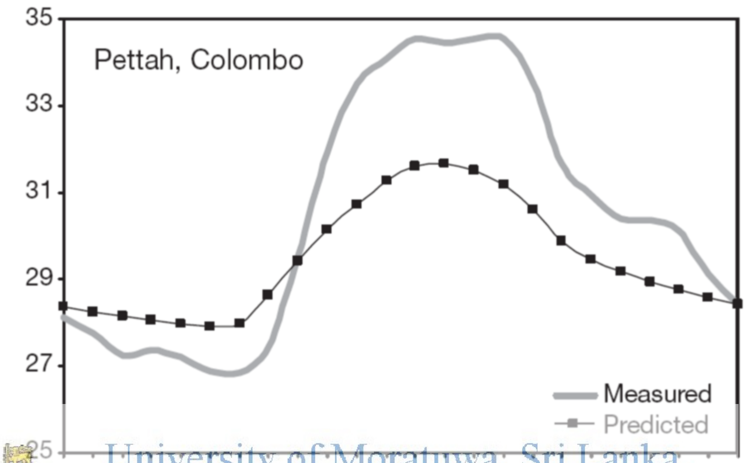


Fig. 32 – ENVI-met - Measured to predicted, Pettah (Colombo)
(Source – Emmanuel & Fernando,2007)

Excessive night-time temperature predictions of ENVI-met were also pointed out in previous works (e.g. Ali-Toudert & Mayer, 2006; Emmanuel et al, 2007; Spangenberg et al, 2008; Janssen, 2006). One reason for the error is the absence of regional exchange processes. This could be significant in the Colombo case where the Indian Ocean lies only 0.5 km northwest of the modelled area. Another reason could be the absence of thermal mass of buildings in the model. Furthermore, it is not possible to change the thermal properties of individual buildings (only an average value for the entire area could be given as a model input). (Emmanuel & Fernando, 2007)

Validation studies was conducted for Colombo, within the confines of the modelled urban area. (Fig. 33) The validation was done for two selected sites on 08.02.2014 and the comparative ENVI-met simulation was completed for the same day. The measurement sites were a part of study by Udawattha & Perera, 2014.

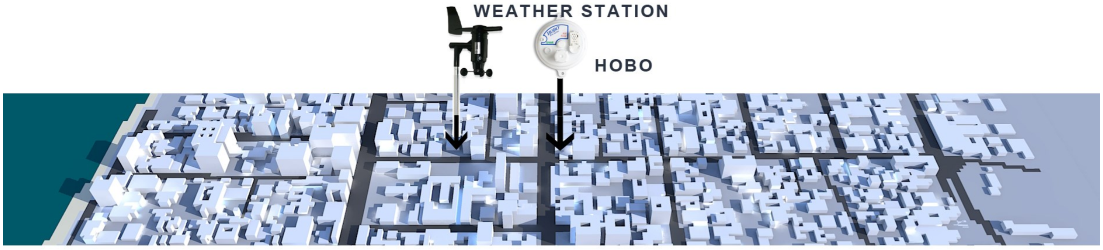


Fig. 33 – Positions of selected sites within representative study area

Weather station site;

The validation uses the Davies Vantage Pro Wireless Weather Station (WS) for data collection. (Fig. 34)

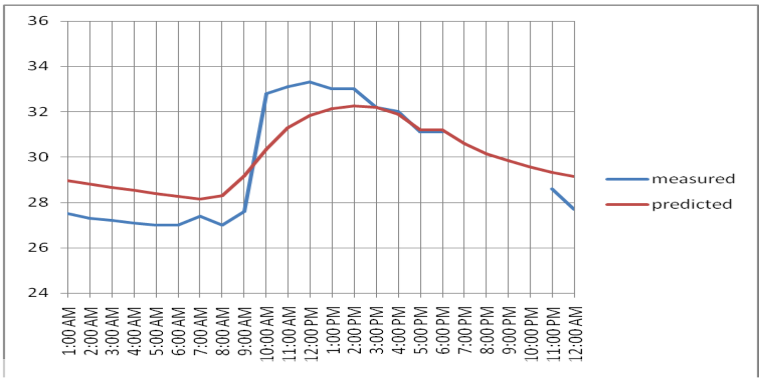


Fig. 34 – ENVI-met - Measured to Predicted (Air Temperature - ^{0}C) - Weather Station (Source - Author)

The model tends to over-predict the air temperature at night (average absolute difference during 19:00 to 05:00 h = 0.38°C; root mean square error RMSE = 1.36° C) and under-predicts during the day (average absolute difference during 07:00 to 17:00 h = 1.03°C; RMSE = 2.84°C). Some hours was lost during the measurement, therefore was excluded in the analysis.

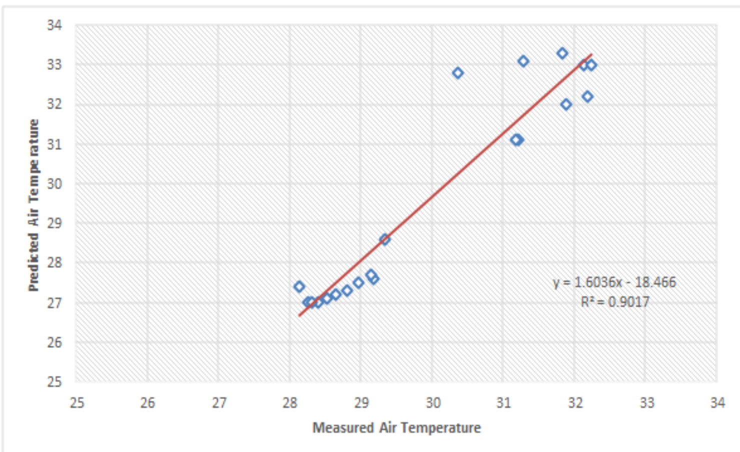


Fig. 35 – ENVI-met - Measured to Predicted (Air Temperature - ^{0}C) - Scatter Plot - WS (Source - Author)

Fig. 35 shows a simple scatter plot to explore the relationship between measured and predicted. The values show a R^2 value of 0.9017 signifying a strong agreement between the two sets of values.

Hobo data logger site;

The data was collected using a HOBO temperature humidity data logger for measurement. (Fig. 36)

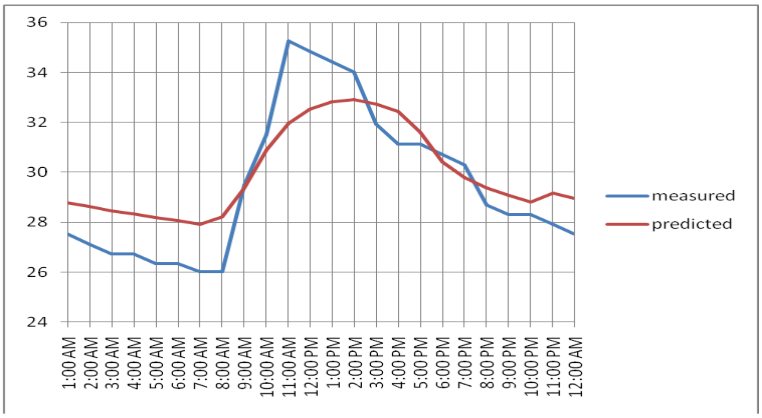


Fig. 36 – ENVI-met - Measured to Predicted (Air Temperature - ^{0}C) - HOBO. (Source - Author)

Here as in the previous measurement sites, the model tends to over-predict the air temperature at night (average absolute difference during 19:00 to 05:00 h = 0.35°C; root mean square error RMSE = 1.99°C) and under-predicts during the day (average absolute difference during 07:00 to 17:00 h = 1.24°C; RMSE = 3.33°C). Fig. 37 shows a 79% agreement between the two data sets. Considering the simplified nature of the model, the similar error patterns in previous and current validation studies for Colombo, it is established that the ENVI-met results are useful even with the above-cited limitations.

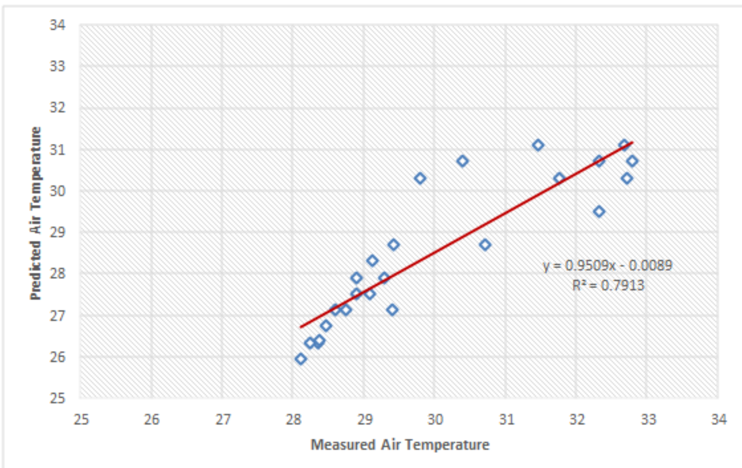


Fig. 37 – ENVI-met - Measured to Predicted (Air Temperature - ^{0}C) - Scatter Plot - HOBO. (Source - Author)

ENVI-met - previous work

ENVI-met has been widely used as the primary tool for microclimate studies in many of the climate zones in the world. The following - Table 11 - is presented as an outline of recent representative sample of the range of application possibilities, validation studies and parameters used for analysis. The major findings of the individual studies are also outlined in Appendix H, as a detailed version of Table 11.

Background Climate Consideration for ENVI-met model - Existing and Globally Warmed climatic contexts

A key consideration for the simulation regime is the input of background climatic input parameters that would generate the envisioned, comparative sensitivity of variables in each of the contexts.

Outlined in Section 3.1.2 of this chapter, is an insight into the existing climate and the project climate under a A2 climate change scenario. In this context, the comparative simulations adopt a 2.4 ^{0}C increase in initial atmospheric temperature as well as initial soil temperatures for the ENVI-met models. Other input data is kept as it is in the existing scenario model. It is deemed that the utilisation of Mean Radiant Temperature (MRT) as the primary variables allows for the consideration of the other parameters in the model. An in-depth definition of MRT is presented later in this chapter.

As (Emmanuel et al., 2007) states "The inter-monsoon period between March and May is the most uncomfortable; temperatures are at their peak, the relative humidity is high and wind speeds low because of the formation of a convergence zone. During this period, the minimum and maximum air temperatures are between about 25 and 32 °C, respectively, and the average relative humidity is around 85%." "The number of hours of sunshine is between 8 and 9 from February to March, and between 6.5 and 7 for the remainder of the year."

Thus, all simulation models adopt the 15th of April (for the year 2013) as the most critical time of the year and therefore the worst-case scenario to be designed for.

Table 11 - Previous work using ENVI-met as primary tool			
Author/s - year	**City**	**Climate zone** (Köppen–Geiger climate classification system)	**Parameter/s studied**
ENVI-met Validation and Simulation Software Combinations			
(Santo, Maggiotto, Stocker, Carruthers, & Di, 2012)	Lecce, Italy	Csa	Validation of ENVI-met / Air temperature
(Francisco, Assis, & Assunção, 2012)	Belo Horizonte, Brazil	Aw	Validation of ENVI-met / Air temperature / Relative Humidity
(C. Peng & Elwan, 2012)	Cairo, Egypt	BWh	Air Temperature / Wind speed / Relative Humidity / MRT / PMV
(Johansson, Spangenberg, Gouvêae, & Freitas, 2013)	São Paulo, Brazil	Cfa/Cwa	Temperature of Equivalent Perception (TEP) / Air Temperature / Wind speed / Relative Humidity / MRT
Vegetation			
(Fahmy & Sharples, 2008)	Cairo, Egypt	BWh	SVF / MRT / PMV
(Yang, Lau, Qian, & Taylor, 2011)	Shanghai, china	Cfa	PET
(Fröhlich & Matzarakis, 2012)	Freiburg, Germany	Cfb	Vegetation / SVF / PET
(Carfan & Galvani, 2012)	São Paulo, Brazil	Cfa / Cwa	PMV / MRT / Wind Speed
(Yuan, Chao, & Edward, 2012)	Beijing, China	Dwa	Wind Speed / PMV
(Srivanit & Hokao, 2013)	Saga, Japan	Cfa	Vegetation / Air temperature
(L. L. H. Peng & Jim, 2013)	Hong Kong	Cwa	Vegetation / PET
Wind			
(Fahmy & Sharples, 2008)	Cairo, Egypt	BWh	SVF / MRT / PMV
(Yuan et al., 2012)	Beijing, China	Dwa	Wind Speed / PMV
Urban Design / Morphology / Building Height			
(Ali-Toudert & Mayer, 2006)	Ghardaia, Algeria	BWh	PET
(Emmanuel & Fernando, 2007)	Colombo, Sri Lanka Phoenix, Arizona, USA	Am / BWh	MRT / Air temperature
(Emmanuel, Rosenlund, & Johansson, 2007)	Colombo, Sri Lanka	Am	MRT / PET
(Rosheidat, Hoffman, & Bryan, 2008)	Phoenix, Arizona, USA	BWh	air temperature / MRT / operative temperature / SET
(Carfan, Galvani, & Nery, 2012)	Ourinhos, São Paulo State, Brazil	Cfa / Cwa	Building height / Air Temperature
(Middel et al., 2012)	Phoenix, Arizona, USA	BWh	LCZ / Air Temperature
(Drach, Emmanuel, & Krüger, 2012)	Glasgow, Scotland	Cfb	Air temperature

<u>Mean Radiant Temperature</u>

Ali-Toudert (2005) defining MRT states:

> A critical issue in assessing the human comfort outdoors is the need for the mean radiant temperature (MRT), which sums up all short-wave and long-wave radiation fluxes absorbed by a human body. MRT is the key variable in evaluating thermal sensation outdoors under sunny conditions regardless of the comfort index used (e.g. Mayer and Höppe 1987, Jendritzky et al., 1990, Mayer 1993, Spagnolo and De Dear 2003). MRT is, per definition, the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual non-uniform enclosure (ASHRAE 2001b). However, its calculation in outdoor spaces is not evident, particularly in complex urban environments. This, certainly, explains the usual focus on air temperature and air humidity in comfort related studies, as these are easier to measure. (Ali-Toudert, 2005)

Theoretically, MRT applicable outdoors is given by the following formula (Fanger 1970);

$$MR = \left[1/\sigma_B \left(\sum_{i=1}^{n} E_i F_i + \frac{\alpha_k}{\varepsilon_p} \sum_{i=1}^{n} D_i F_i + \frac{\alpha_k}{\varepsilon_p} f_p I \right) \right]^{0.25}$$

Where the surroundings are divided into n isothermal surfaces. For each of these surfaces;

E_i	Wm^{-2}	$E_i = \sigma_B \mathcal{E}_i T_i^4$	long-wave radiation component
D_i	Wm^{-2}		diffuse and diffusely reflected short-wave radiation
F_i			angle weighting factor
I	Wm^{-2}		direct solar radiation impinging normal to the surface
f_p			surface projection factor which is a function of the sun's position and the body posture
α_k		(≈ 0.7)	absorption coefficient of the irradiated body surface for short -wave radiation
$\mathcal{E}_p$		(≈ 0.97)	emissivity of the human body
σ_B		($5.67.10^{-8} W/m^{-2}K^{-4}$)	Stefan–Boltzmann constant

The calculation of the angle-weighting factor Fi is the most problematic aspect when dividing the environment into several surfaces. A procedure for calculating the angle factors is given by (Fanger 1970) for simple shapes, but the task becomes much more complicated for complex urban forms. Simplifications are thus necessary. (Ali-Toudert, 2005)

Ali-Toudert & Mayer, (2006) states: “To date, there is no reliable instrument for integral measurement of MRT outdoors, even though a number of tests have been made, e.g. (Krys & Brown, 1990). An accurate on-site measurement technique exists [(VDI, 1998), (Höppe, 1992)] including all radiation fluxes, angle factors, human shape, etc., but it is costly and time-consuming.” In this respect, ENVI-met gives a good approximation of MRT at street level (Bruse, 1999) (Ali-Toudert & Mayer, 2006)

3.3.2 Simulation Matrix - Site definition, existing and projected morphology

<u>Site definition</u>

With the research focus on Colombo, Sri Lanka as a case study - simplification and mapping of LCZs; application of SHIM for local warming implications of LCZs; and the identification of critical LCZs for further study - the primary task here is to select representative urban blocks to test the effects of changing morphology on the sensitivity of parameters (defined later in the chapter in Table 14).

Fig. 38 – Selected site area - shows open spaces and major roads . (Source - Google Earth)

Thus, the representative site selected encompasses the critical LCZs identified in the previous section. It also cuts across Colombo's main transport arteries; Marine Drive, Galle Road, R A de Mel Mawatha and Havelock Road. The main roads are North / South oriented. The selected area also includes Dickman's Road as a significant east/west oriented street. A distinct pattern of minor streets allows for the clear definition of urban plots. The site has the Indian Ocean to the west and one of the largest open spaces, the Havelock park area to the east. The selected area has varying density, surface and vegetation cover characteristics that augment the selection as a representative area for warm humid Colombo. (Fig. 38). A detailed description of sites selected shown in Fig. 39 and Fig. 40. Site details and morphology, measurement points, for all simulation cases are presented in Fig. 41, Fig. 42, Fig. 43, Fig. 44, Fig. 45 and Fig. 46.

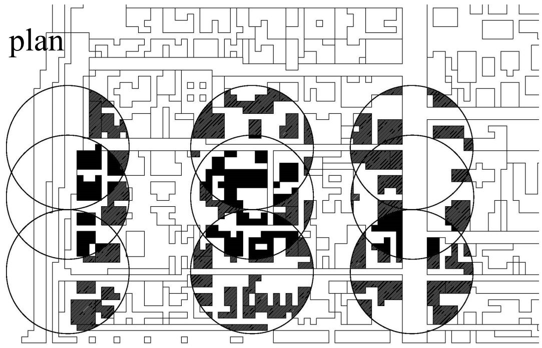
Existing and projected morphology

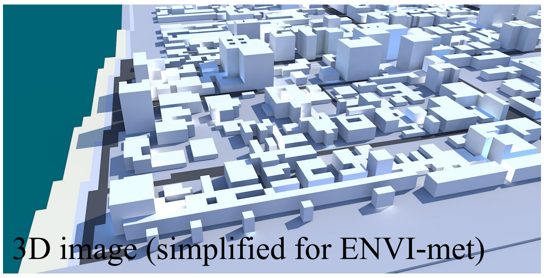
The morphology changes draw on previous work relating to canyon geometry and urban block shape. These concepts are simplified to examine their overall effect. The shadow umbrella concept is a prominent example.

The objective is to explore a systematic variation in morphology to ascertain the effect of individual urban morphology variables on the Mean Radiant temperature (MRT).

- Variation is limited to the range between the maximum LCZ3 to the maximum allowable for LCZ2
- Options keep within selected LCZs only. Thus, restricting a LCZ change that will drive the UHI intensity up, as seen in the LCZ classification analysis.
- They explore a change in the surface cover of the non-built areas of an urban block. Where, the open surfaces are simulated two cases one with open soil and the other with a 'grass' cover.
- The built surface fraction is kept constant for all morphology options.
- Tree cover and vegetation in the urban environment is recognised as important, yet, it is not explored. This is due to the fact that the research focuses on the morphology changes, which can be used to ameliorate the urban outdoors and can be controlled by urban design.

The following matrix of cases shown in Table 12 strives to paint a clearer picture. The matrix outlines the options simulated. Overall the 96 individual ENVI-met models encompass a combination of 4 cases, 4 sites and 6 models. Each model had 9 receptor points to explore temperature variations within the model, generate 864 data sets (or points of measurement) for analysis. (Fig. 41, Fig. 42, Fig. 43, Fig. 44, Fig. 45 and Fig. 46). Influence on receptor points assumed as a circle of 100m diameter as shown in the figures. (Appendix I - Morphology / Physical Details of Receptor Point Data)

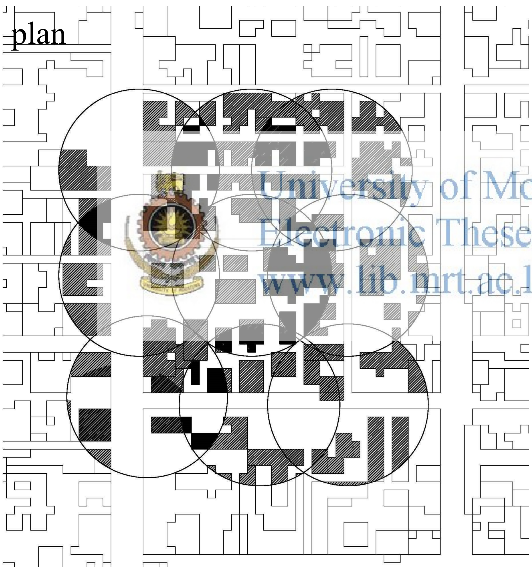


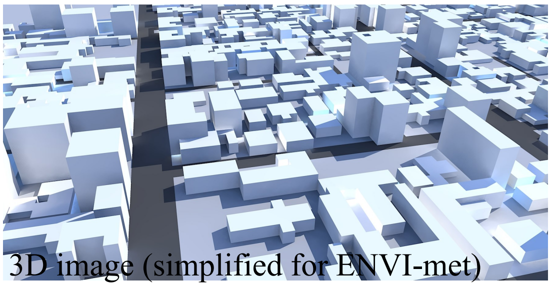


Site 01

Between the Sea / Marine drive and Galle Road

(circles show receptor points - it is assumed that each receptor point encompasses an influence area of 100m diameter)



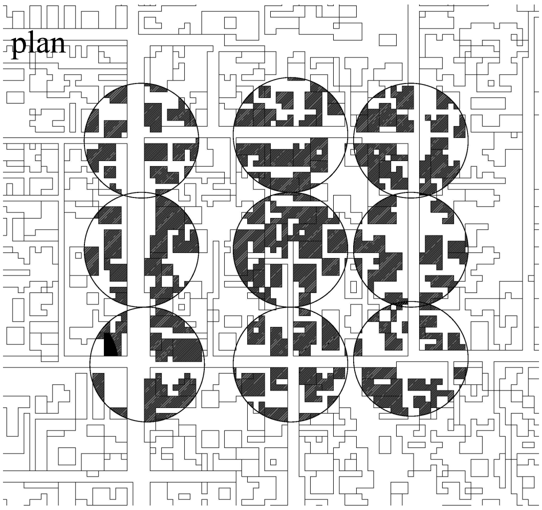


Site 02

Between Galle Road and R A De Mawatha

(circles show receptor points - it is assumed that each receptor point encompasses an influence area of 100m diameter)

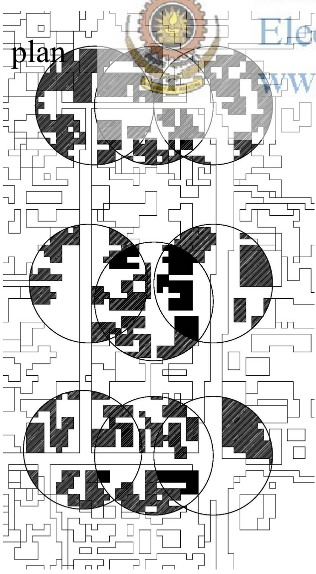
Fig. 39 - Simulation Site01 and Site02 (Source - Author)

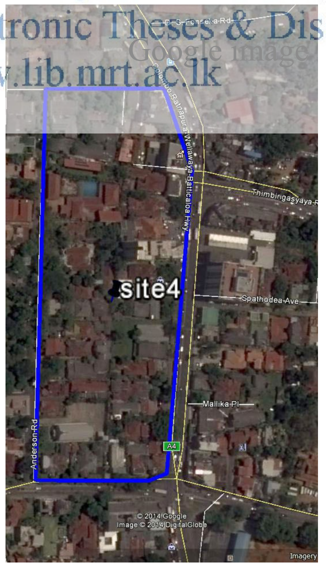


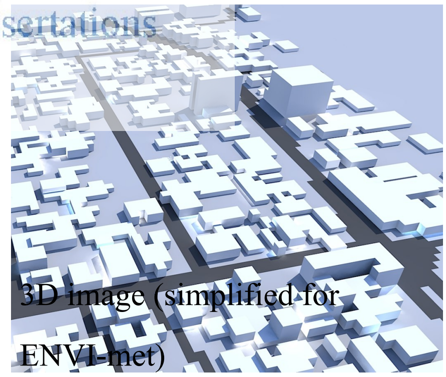
Site 03

Between R A De Mawatha and Havelock Road - R A de Mel Mw edge.

(circles show receptor points - it is assumed that each receptor point encompasses an influence area of 100m diameter)







Site 04

Between R A De Mawatha and Havelock Road - Havelock Rd edge.

(circles show receptor points - it is assumed that each receptor point encompasses an influence area of 100m diameter)

Fig. 40 - Simulation Site03 and Site04. (Source - Author)

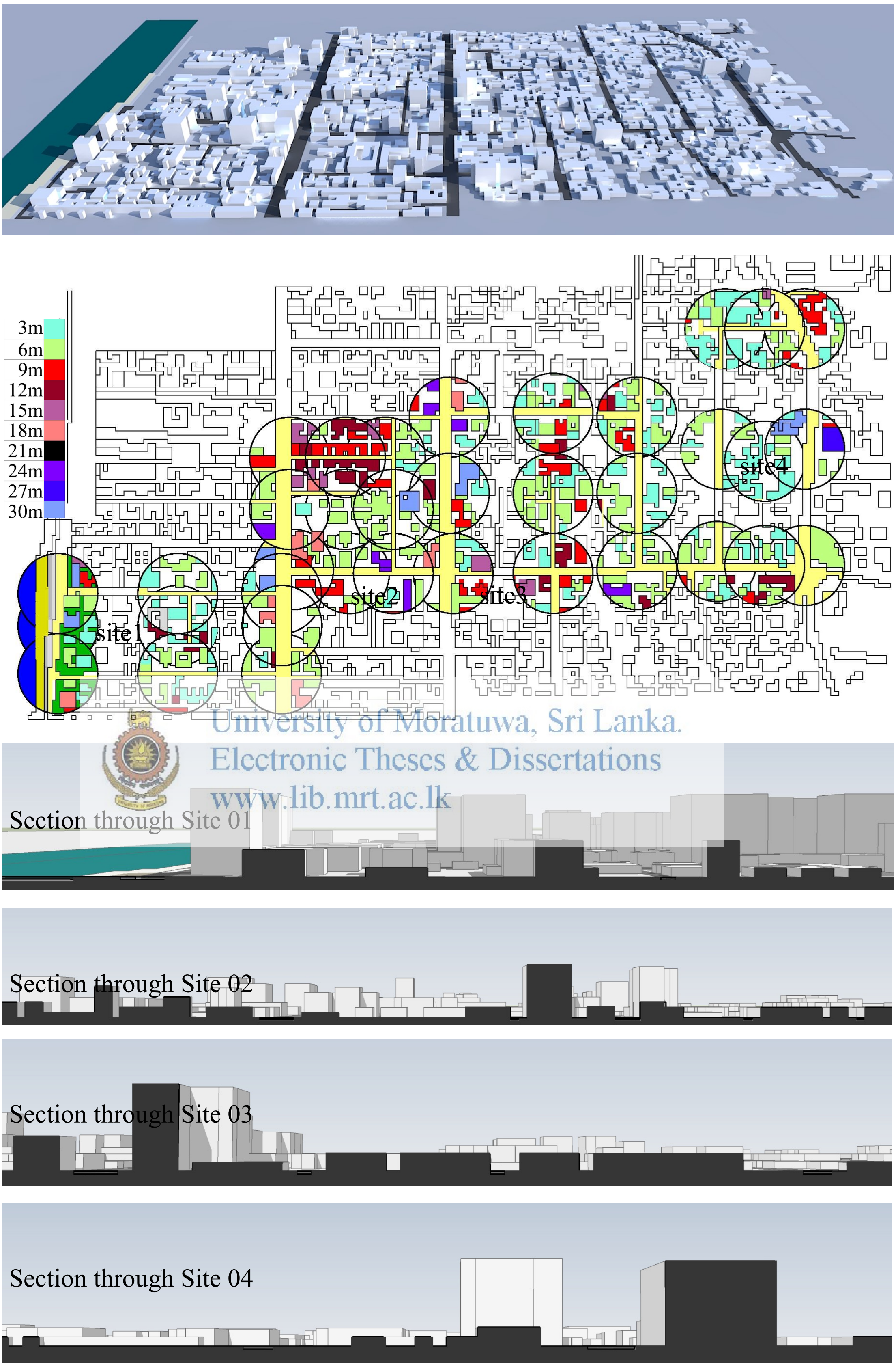


Fig. 41 - Existing Buildings (all sites) - m1. (Source - Author)

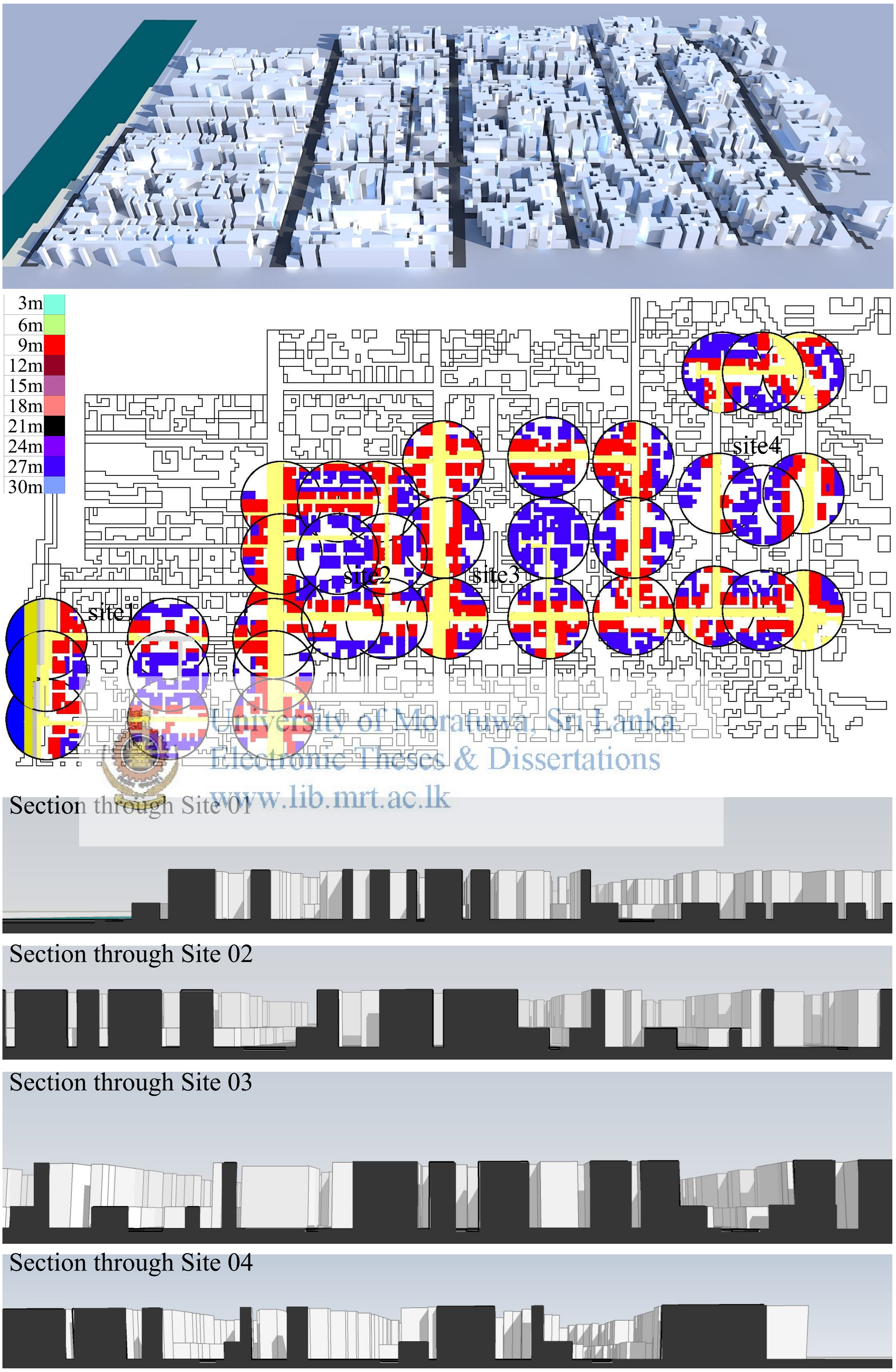


Fig. 42 - High centre (all sites) - m2. (Source - Author)

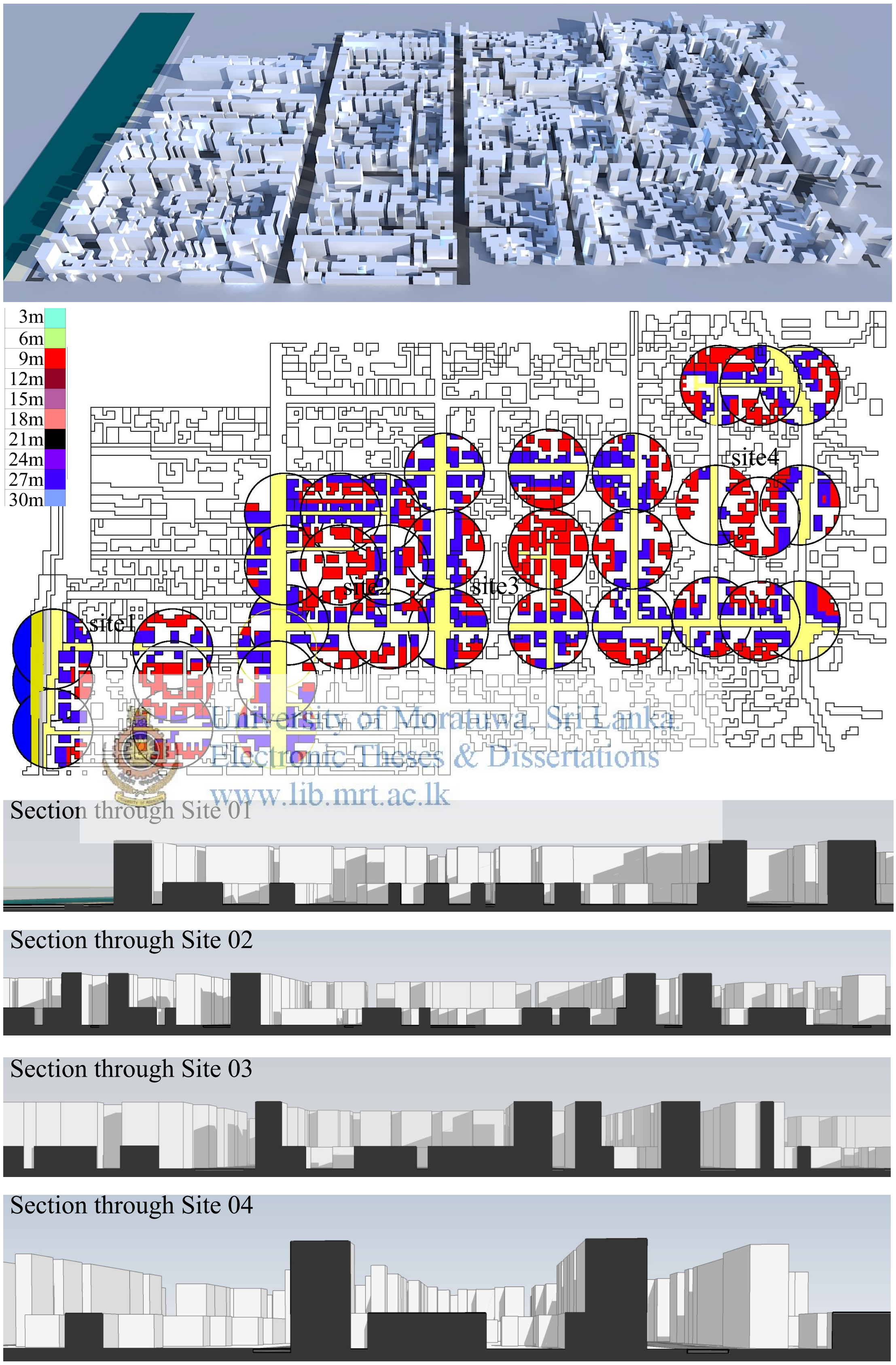


Fig. 43 - High edge (HE) (all sites) - m3. (Source- Author)

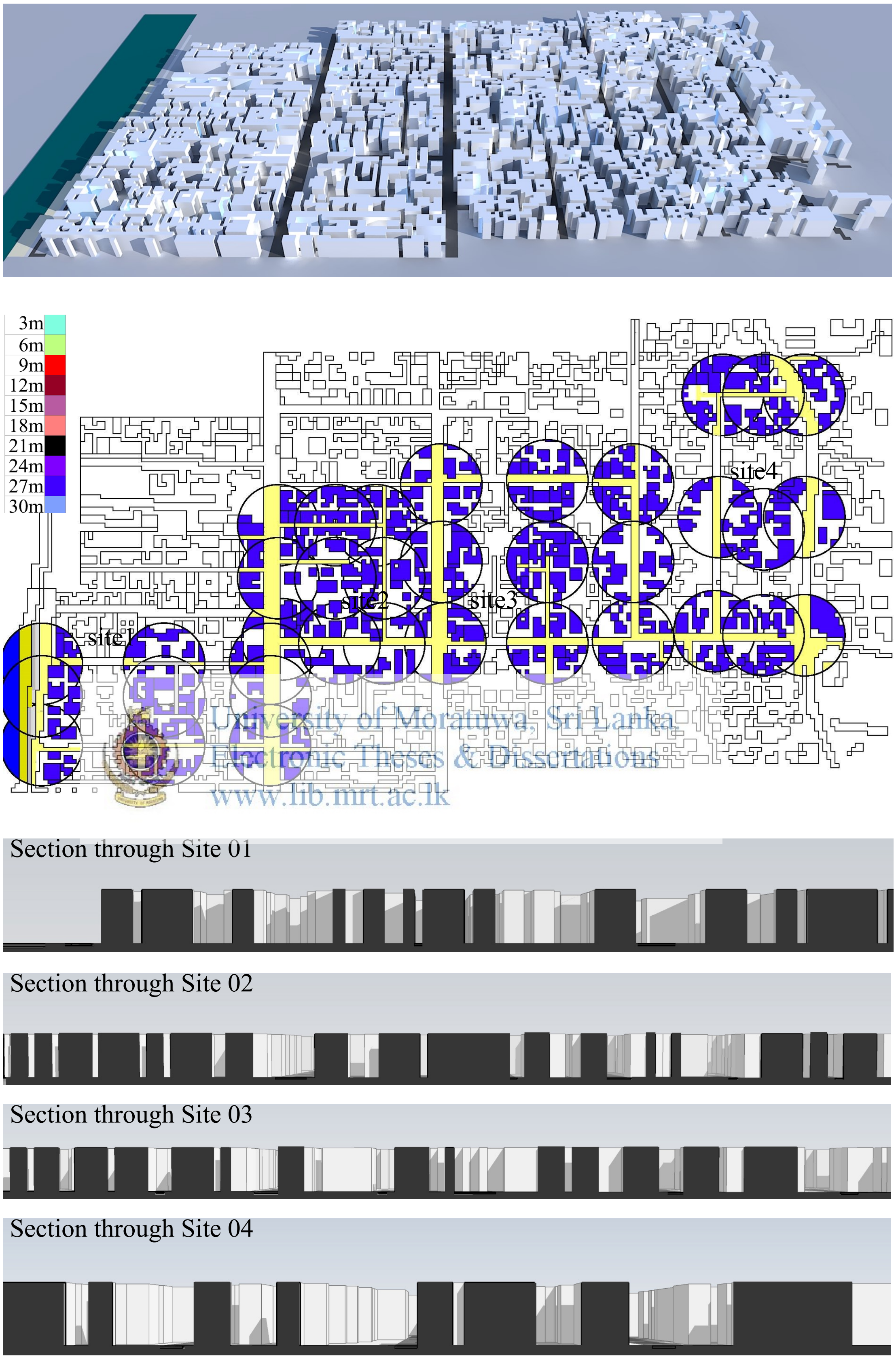


Fig. 44 - LCZ2 (all sites) - m4. (Source - Author)

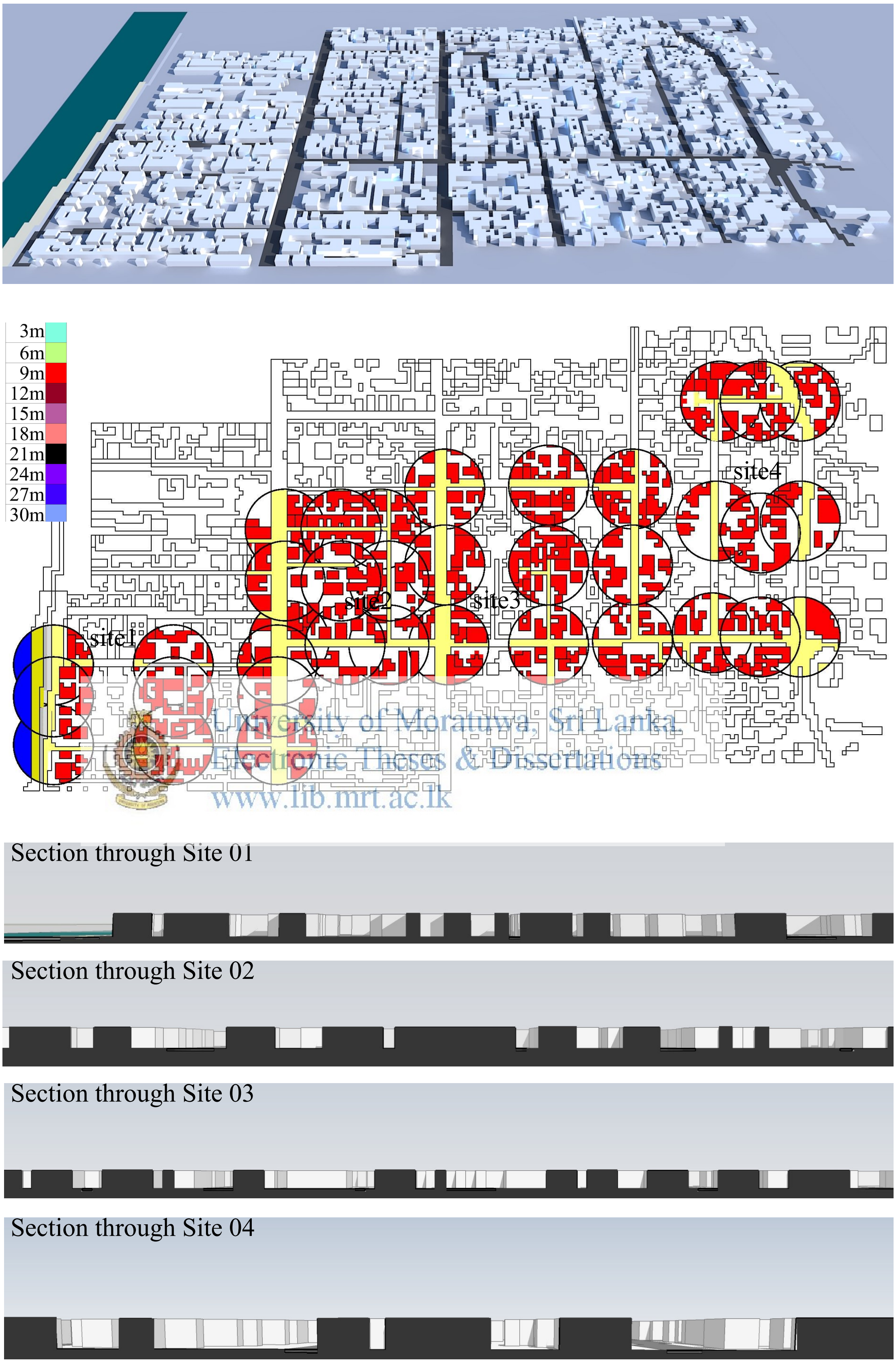


Fig. 45 - LCZ3 (all sites) - m5. (Source - Author)

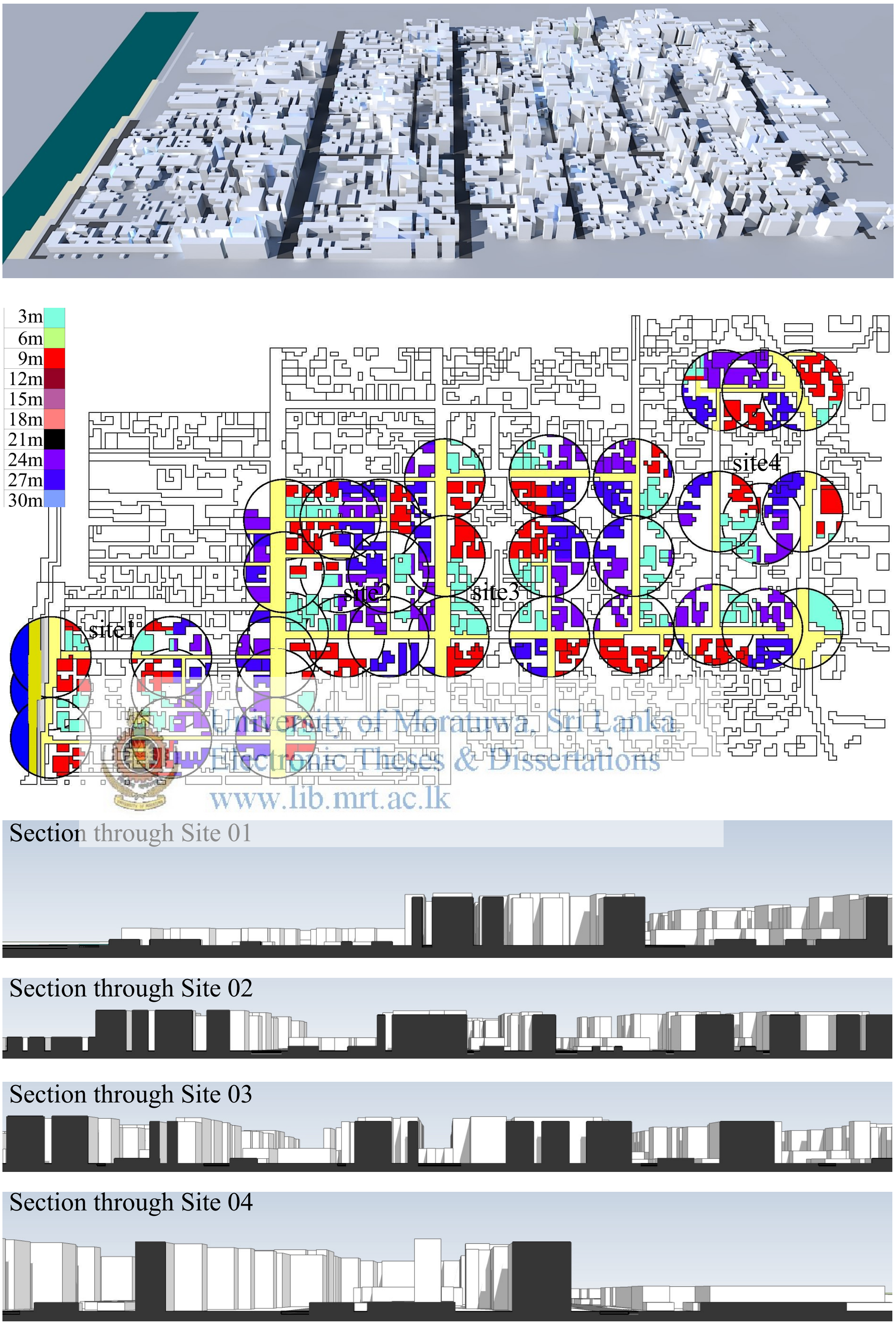


Fig. 46 - Shadow umbrella (all sites) - m6. (Source - Author)

Table 3.9 - ENVI-met Simulation Matrix

Cases (x4)		Site (x4)		Model(x6)		Receptor points (x9)		Streets (x5)	
Case 1 (case1)	Models existing background microclimate conditions. Pervious surfaces are open soil	Site 1 (site1) (Fig. 3.24)	Site between marine drive / Galle road	Base case (m1) (Fig. 3.26)	urban blocks and buildings are as existing	centre (r1)	Receptor point - a term generic to ENVI-met, denotes a measurement site in the simulation model. The simulation software generates specific data for each receptor point included. The rest of the output remains a part of the whole. The receptor points for each simulation model are in the cardinal directions as well as at the centre of the urban block.	centre (c)	Receptor points are amalgamated to create street profiles that bound a particular urban block. The street nomenclature depicts the boundaries of the block, together with the centre of the block. See (Fig. 4.22)
Case 2 (case2) (g)	Models existing background microclimate conditions. Pervious surfaces are 50mm average density grass	Site 2 (site2) (Fig. 3.24)	Site between Galle road / R A de Mel Mw (Galle road edge)	High centre (m2) (Fig. 3.27)	Blocks simplified as 9m street edges with 27m centre of the blocks. The models assume 15m of the block edge to be 9m.	East (r2)		North-South East facing (ns e)	
Case 3 (case3) (gw)	Models 'warmed' background microclimate conditions. Pervious surfaces are open soil	Site 3 (site3) (Fig. 3.25)	Site between Galle road / R A de Mel Mw (R A de Mel Mw edge)	High edge (m3) (Fig. 3.28)	Blocks simplified as 27m street edges with 9m centre of the blocks. The models assume 15m of the block edge to be 27m.	North (r3)		North-South West facing (ns w)	
Case 3 (case4) (ggw)	Models 'warmed' background microclimate conditions. Pervious surfaces are 50mm average density grass	Site 4 (site4) (Fig. 3.25)	Site between R A de Mel Mw / Havelock road (Havelock road edge)	Lcz2 (m4) (Fig. 3.29)	Simplified Blocks assume maximum and uniform building height of 27m.	West (r4)		East-West North facing (ew n)	
				Lcz3 (m5) (Fig. 3.30)	Simplified Blocks assume minimum and uniform building height of 9m.	South (r5)		East-West South facing (ew s)	
				Shadow umbrella (m6) (Fig. 3.31)	Blocks assume a simplified shadow umbrella form. The blocks assume 4 distinct zones as follows; Southwest - 3m Northwest - 9m Northeast - 27m Southeast - 24m	Northeast (r6)			
						Northwest (r7)			
						Southeast (r8)			
						Southwest (r9)			

3.3.3 Analysis Protocol

The primary objective is to analyse the behaviour and sensitivity of the morphology variables in relation to the MRT of the urban outdoors. IBM SPSS (Statistical Package for the Social Sciences) - Statistics - Version 22 is utilised for this purpose.

IBM SPSS is a widely used program for statistical analysis. Here it is used mainly for Bivariate and Linear Regression statistical analysis, with MRT as the dependent variable. It is also used to generate graphs (regression plots) that will allow comparison and prediction.

Regression analysis was used as the main tool to explore the relationship between urban planning indicators (termed morphology variables in this study) and climate indicators was adopted by researchers like (Giridharan, 2005), (Zhao et al, 2011), (Yang et al, 2010) and, (Srivanit & Kazunori, 2011b)

The Pearson's correlation coefficient and 1-tailed test of statistical significance is used for analysis in all cases.

Chok (2010) states:

> The Pearson's correlation coefficient is a common measure of association between two continuous variables. It is defined as the ratio of the covariance of the two variables to the product of their respective standard deviations, commonly denoted by the Greek letter ρ (rho):
>
> $$\rho = \frac{Cov(X,Y)}{\sigma_X \sigma_Y}$$
>
> The Pearson's correlation coefficient ranges from -1 to +1. A positive monotonic association (two variables tend to increase or decrease simultaneously) results in $\rho > 0$, and negative monotonic association (one variable tends to increase when the other decreases) results in $\rho < 0$. ρ of 0 corresponds to the absence of the monotonic association, or absence of any association in the case of bivariate normal data. However, for bivariate distributions other than bivariate normal distribution, the Pearson's correlation

can be zero for dependent variables. For example, it can be '0' for the variables with non-monotonic relationship, e.g. $Y = X^2, (x \in (-1, 1))$

The absolute value of ρ indicates the strength of the monotonic relationship between the two variables. ρ of 1 indicates a perfect linear relationship, i.e. Y = a+bX. (Chok, 2010).

The strength of the relationship is better seen as follows;

If Pearson r =

+.70 or higher	-	Very strong positive relationship
+.40 to +.69	-	Strong positive relationship
+.30 to +.39	-	Moderate positive relationship
+.20 to +.29	-	Weak positive relationship
+.01 to +.19	-	No or negligible relationship
-.01 to -.19	-	No or negligible relationship
-.20 to -.29	-	Weak negative relationship
-.30 to -.39	-	Moderate negative relationship
-.40 to -.69	-	Strong negative relationship
-.70 or higher	-	Very strong negative relationships

1-tailed test is used for the reason that the analysis seeks to establish a clear understanding if there is a difference and if so, is it higher or lower.

Data variables

The data generated in ENVI-met is combined with those of the urban context (calculated manually - Appendix I) to form a dataset that encompass variables shown in Table 13.

The inclusion of the morphology variables is in line with the approach to adopt the LCZ classification as a basis for simplification. The variables are as defined as the range of values of geometric and surface cover properties inherent in each LCZ shown in Appendix C.

Table 13 - ENVI-met output variables - Definitions and Description

Variable	Unit	Definition	Description
Climatic Variables			
u	m/s	Wind speed u-component (west to east)	The minus sign in front of the U component answer indicates an easterly component to the wind, or in other words, a wind that blows from east to west. A positive U component would mean that the wind is blowing from west to east.
v	m/s	Wind speed v-component (south to north)	The positive V component answer indicates a southerly component to the wind, or in other words, a wind that blows from south to north. A negative V component would mean that the wind is blowing from north to south
w	m/s	Wind speed w-component (vertical)	
wSpeed	m/s	Total wind speed	
wDir		Wind direction	0=North, Rotation corrected
T	K	Air temperature	
q	g/kg	Specific Humidity Air	
q.rel		% Relative Humidity Air	
MRT	K	Mean Radiant Temperature	
Urban fabric data - Urban morphology variables			
SVF.bldg	SVF	Sky-View factor (only buildings) Ratio of the amount of sky hemisphere visible from ground level to that of an unobstructed hemisphere	The SVF is considered for buildings only. The models exclude street trees in the simulation, as the focus is only on the morphology aspects of the fabric.
Building surface fraction	BSF	Ratio of building plan area to total plan area (%)	Remains constant for all simulations
Impervious surface fraction	ISF	Ratio of impervious plan area (paved, rock) to total plan area (%)	
Pervious surface fraction	PSF	Ratio of pervious plan area (bare soil, vegetation, water) to total plan area (%)	
Green surface fraction	GSF	Ratio of pervious plan area (bare soil, vegetation, water) to total plan area (%)	PSF is replaced by GSF where the simulation models adopt 'grass cover' in place of 'open soil'

Table 14 - Data Analysis Series - Description and Objectives

Series (Section in Chapter 4)		Description	Relationship to study objective
Total Case series (Section 4.1)	Total (24 hrs.)	The series analyses variables for all sites, models and receptor points, under specific climatic background conditions.	The objective is to ascertain the overall sensitivity of the variables, within a varied combination of patterns.
	Day (4.1.2)	As above. The data included is for the daytime hours between 6.00 to 18.00hrs.	As above. Explores the sensitivity of variables for the sunshine hours of the day.
	Night (4.1.3)	As above. The data included is for the daytime hours between 0.00 to 6.00hrs and 18.00 to 0.00hrs.	As above. Explores the sensitivity of variables when the sun's influence is not present.
	Peak (13.00hrs) (4.1.4)	As above.	As above. Explores the sensitivity of variables for the warmest hour of the day.
Site Case series (Section 4.2)		The series analyses variables for specific sites. Includes all models and receptor points, under specific climatic background conditions.	The objective is to see if the correlations of the variables change for different sites in the urban context.
Model Case Series (Section 4.3)		The series analyses differing morphology models and their correlation to MRT change. Includes all sites and receptor points.	The objective to see 'if' and therefore 'how' the changing background conditions effect the correlation between the morphology variables and MRT.
Receptor case series (Section 4.4)	As Individual receptors (4.4.1)	Explores the variable correlation for individual receptor points. The analyses include all sites.	How do individual receptors for a simulated urban block compare, under varying background conditions.
	As Street orientation (4.4.2)	As above. Simplifies / amalgamates the receptors to represent a certain street / urban canyon characteristic. Explores the variable correlation for the center of the block and street orientation. The analyses include all sites.	As above. How do the differently oriented streets compare in their correlation of variables with MRT?

The total data set is then categorised into selected cases to focus on a series of scenarios for analysis, comparison and better understanding of the sensitivity of morphology variables under different conditions. These data analysis series are as defined in Table 14 and also outlines the objective of each analysis series in its relationship to the study.

Sections that present the Results and Discussion in Chapter 4 are indicated in the matrix, for clarity.

The dependent variable in all of these scenarios is the MRT value of the urban outdoors.

Summary

The chapter encompassing the Research Design, approached the task in creating the needed impetus to answer the research questions generated in Chapter 2 of this thesis.

As stated at the outset of this chapter, the results and analysis of each of the prior questions and therefore output data, feed the next question and establishes the input data and parameters. In this regard, the chapter included the 'Mapping of LCZs and constituent Local warming effects' as an essential part of the research design.

The research design for the 'Sensitivity Analysis' of the parameters encompassing those defined in the LCZ classification and focused on the morphology variables are defined in Section 3.3. The chapter concludes in defining an analysis protocol utilising statistical tools to identify comparative patterns in the existing climatic context as well as in a globally warmed background in the year 2100.

4.0 Results and Discussions

The analyses encompasses a series of scenarios where the primary objective is to ascertain the sensitivity of specific variables, in a changed microclimate. The research is focussed on warm humid Colombo, Sri Lanka as a case study. Mean Radiant Temperature (MRT) is taken as the indicator of thermal comfort in the urban outdoors in general and streets as public spaces in particular.

The data generated by the ENVI-met simulation models and manual calculation (as defined in Table 14) are first analysed utilising Bivariate Analysis to determine the relationship between the variables and MRT. The tables presented for each case series in the presentation of analysis data, extracts these individual case analysis and tabulates them for comparative clarity. It is discussed in terms of the correlation of variables and statistical significance to MRT.

MRT to Time relationship is communicated using regression curve fits to plots the relationship. As in the bivariate analysis, individual analysis results are superimposed graphically to produce a comparative image for clarity of communication.

As detailed in Section 4.1.1, multiple regression and stepwise regression is used to identify the most prominent variables effecting MRT in the urban outdoors for thermal comfort and UHI mitigation. Here, as in the previous presentation of analysis data, individually generated data are tabulated for comparative purposes.

4.1 Total Case Series - Total, Day, Night and 13.00hrs. analysis

The main objective of the analysis is to ascertain the association of the variables of urban morphology that can be controlled by urban design, with that of the changing background climate conditions.

The cases, as defined in Table 14encompass;

- case1 - existing background climate with open soil (in pervious areas)

Table 15: Total Case Series - Correlation of Variables to Mean Radiant Temperature

case		u	v	w	wSpeed	wDir	T	q	q.rel	SVF	BSF	ISF	PSF	GSF	HRE	FAR
case1	Correlation	-.022	-.046**	.035**	.039**	-.018	.843**	.729**	-.614**	.145**	-.074**	.073**	-.018		-.100**	-.123**
	Significance	.054	.001	.006	.002	.094	0.000	0.000	0.000	.000	.000	.000	.102		.000	.000
case2	Correlation	-.025*	-.047**	.030*	.040**	-.015	.842**	.728**	-.607**	.145**	-.074**	.074**	-.018	-.050**	-.100**	-.124**
	Significance	.037	.000	.016	.002	.137	0.000	0.000	0.000	.000	.000	.000	.102	.000	.000	.000
case3	Correlation	-.021	-.050**	.041**	.044**	-.018	.844**	.730**	-.536**	.159**	-.083**	.082**	-.019		-.111**	-.136**
	Significance	.063	.000	.002	.001	.094	0.000	0.000	0.000	.000	.000	.000	.087		.000	.000
case4	Correlation	-.024*	-.051**	.039**	.045**	-.012	.843**	.728**	-.524**	.160**	-.084**	.083**	-.019	-.056**	-.110**	-.137**
	Significance	.041	.000	.003	.001	.187	0.000	0.000	0.000	.000	.000	.000	.086	.000	.000	.000

**. Correlation is significant at the 0.01 level (1-tailed).

*. Correlation is significant at the 0.05 level (1-tailed).

- case2 - existing climate background with green (50mm of grass) surface cover (in pervious areas)
- case3 - globally warmed climate background with open soil (in pervious areas)
- case4 - globally warmed climate background with green (50mm of grass) surface cover (in pervious areas)

The main emphasis being the correlation to Mean Radiant Temperature (MRT) as the dependent variable in all cases. The results compare all sites, models and receptor points, particular to each case. The Pearson's correlation coefficient and 1-tailed test of statistical significance is used for analysis in all cases as defined in section 3.2.4

Correlation Analysis -

Table 15 shows the comparative correlation of MRT for each climate background case. The data used for the analysis encompasses all sites, models and receptor points, defined in the previous section.

It is observed for most of the variables, the correlation coefficient is weak. The morphology variables (SVF, BSF, ISF, PSF, GSF, HRE, FAR) in particular have 'no or negligible relationship' to MRT.

A very strong correlation, (either positive or negative) is seen in - temperature (T), Specific humidity (q). A strong correlation is seen in - Relative humidity (q.rel)

Comparatively, correlations increase for the Global Warming cases (case2 and 4) over the existing background cases, approximately in the 0.01 range. Yet, the changes are not distinct enough to do not exceed the correlation levels. 'Green cases' for both existing (case2) (g) and global warming (case4) (ggw) background conditions have minimal or no impact on the MRT change. This is seen for all variables considered.

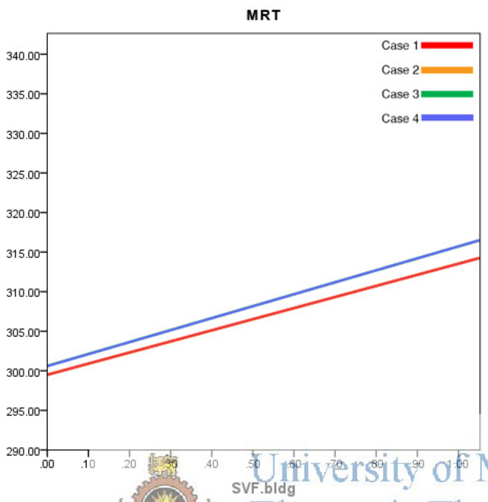
Statistical Significance -

Most variables are statistically significant, with p-value < 0.001 for most morphology variables considered. The variables u, wDir, PSF are not statistically significant.

Relationship between Mean Radiant Temperature and Urban Morphology Variables

Sky-view factor (SVF) -

SVF demonstrates a positive correlation with MRT. The differences between the cases show an increase in the rate of change for the global warming cases. The green cases do not show significant change in comparison. SVF has the strongest correlation to MRT in comparison to the other variables that can be changed by urban design is concerned. (Fig. 47)



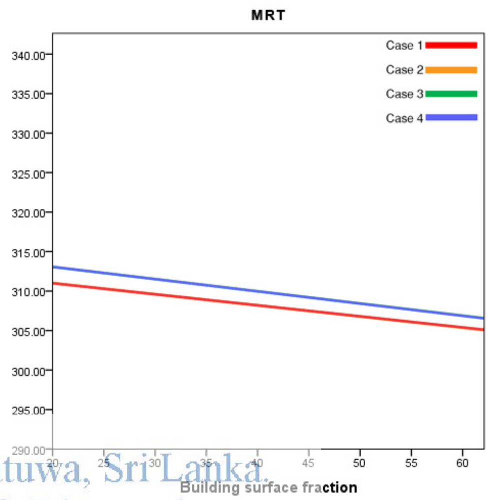


Fig. 47 - SVF to MRT relationship

Fig. 48 - BSF to MRT relationship

Building surface factor (BSF)-

BSF demonstrates a negative correlation with MRT. The differences between the cases show an increase in the rate of change for the global warming cases. The green cases show minimal or no change. (Fig. 48)

Impervious surface factor (ISF)-

ISF demonstrates a positive correlation with MRT. The differences between the cases show only a minute increase in the rate of change for the global warming cases. (Fig. 49)

Pervious surface fraction (PSF)-

PSF is not significant as per the Pearson correlation matrix generated in the analysis. There is minimal or no change in the correlation across the different models, therefore the rate of change, remains almost constant.

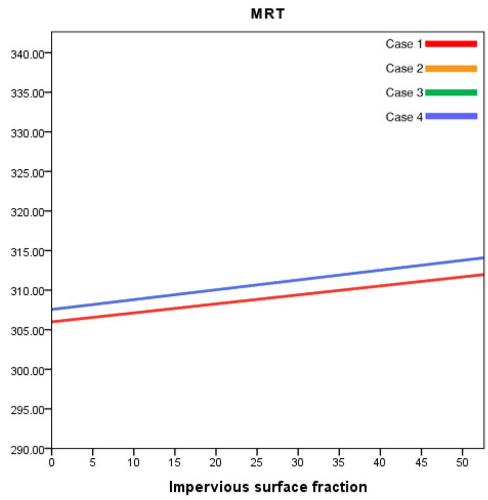


Fig. 49 - ISF to MRT relationship

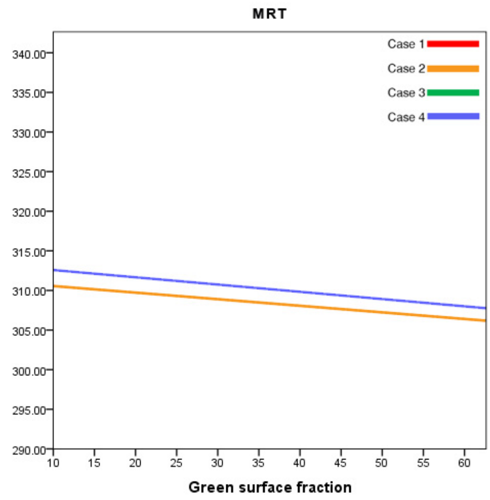


Fig. 50 - GSF to MRT relationship

Green surface factor (GSF)-

GSF demonstrates a negative correlation with MRT, therefore with an increase in GSF the MRT intensity is reduced. This factor is known in many studies and as highlighted in Section 2.5 the surface temperature of a comparative green surface can help reduce MRT. The differences between the cases show only a slight increase in the rate of change for the global warming case. (Fig. 50).

Height of roughness elements (HRE)-

HRE demonstrates a negative correlation with MRT. The differences between the cases show an increase in the rate of change for the global warming cases. The

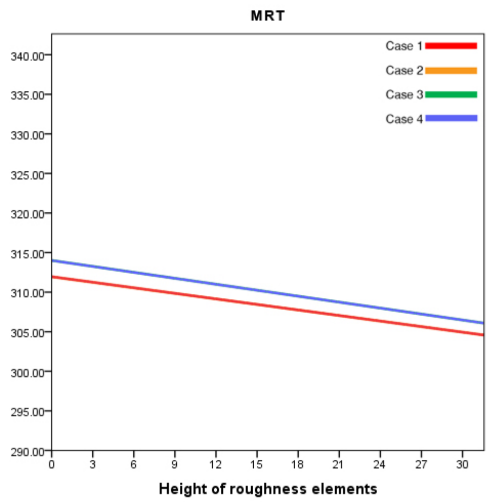


Fig. 51 - HRE to MRT relationship

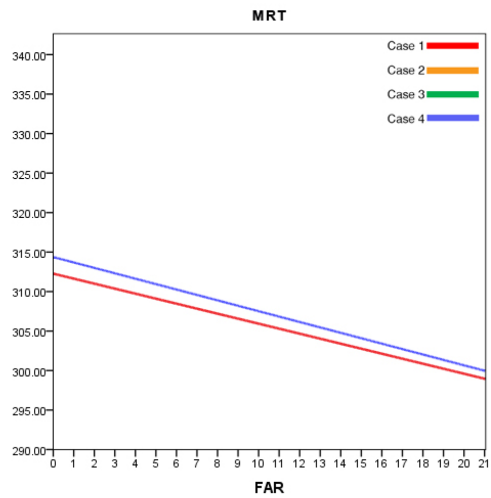


Fig. 52 - FAR to MRT relationship

green cases follow a similar trend, where there is no effect in comparison to the existing background cases. (Fig. 51)

Floor area ratio (FAR)-

The Floor area ratio (FAR) demonstrates a negative correlation with MRT. The differences between the cases show a slight increase in the rate of change for the global warming cases. The green cases follow a similar trend as stated above. (Fig. 52)

Discussion

Overall, the variables that could be controlled by urban design, have an impact on the MRT intensity in the microclimate. The correlation is strongest for SVF in relation to the morphology variables considered. The effect of the changing morphology is clear. An increased ability for the built fabric to create shade (BSF, HRE, FAR) and reduced exposure to the solar radiation in terms of SVF, results in a reduction in the MRT intensity. In consideration of the surface characteristic variables an increase in GSF is beneficial.

Analysis of data using a regression curve fit is shown in Fig. 53 (R^2 value of 0.016). Comparative interpolated lines for cases show two distinct trends, that of the existing cases and those of the global warming cases. The green cases of the

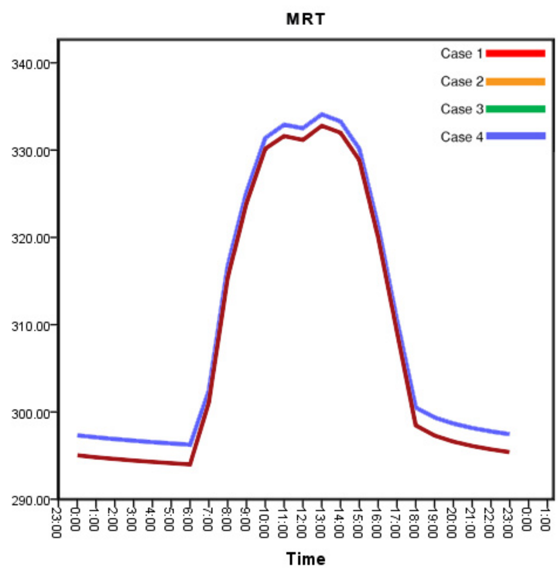


Fig. 53 - All cases - MRT to Time relationship

climatic backgrounds show no change and thus follow a similar trend to the open soil cases.

The effect of the change in MRT between existing and global warming cases is clear in the nighttime hours and to a lesser extent in the middle of the day. The peak MRT occurs at 13.00 hrs. It is interesting to note that the hours in the day where the microclimate warms and cools, overlap for both existing and global warming cases.

4.1.1 Relationship between urban morphology variables and climate variables to Mean Radiant Temperature (MRT)

The **multiple regression method** is used to explore the relationship between all variables and MRT. Here the categorical variables in the data set are excluded. The 'Time' variable although deemed significant is also not taken into the regression model. The focus therefore is only on the morphology and climate variables. Table 16 shows the comparative coefficients for the four background condition cases that are simulated.

The variables entered (Table 16) can explain 73.6% to 74.1% of the MRT change in the urban outdoors for the different cases. The applicability of the variables shows an increase in R^2 value for the global warming background scenarios. The significance level of variables differs between models. Yet, in all models, the Impervious Surface Fraction (ISF) is dropped.

The **stepwise regression method** is used to explore the strongest relationship between the variables and MRT. (Table 17) Stepwise regression is a modification of the forward selection so that after each step in which a variable was added, all candidate variables in the model are checked to see if their significance has been reduced below the specified tolerance level. If a non-significant variable is found, it is removed from the model. Stepwise regression requires two significance levels: one for adding variables and one for removing variables. (NCSS Statistical Software, n.d.) The criteria used; probability of F to enter <= 0.05 and probability of F to remove >= 0.100.

Table 16 - Regression results of the overall MRT

Description/variables	Case1			Case2			Case3			Case4		
	Coefficients		Sig. level	Coefficients		Sig. level	Coefficients		Sig. level	Coefficients		Sig. level
	B	Beta		B	Beta		B	Beta		B	Beta	
U	.455	.006	.548	.653	.008	.412	.413	.006	.571	.503	.007	.512
V	8.797	.280	.000	9.221	.289	.000	8.080	.262	.000	8.454	.269	.000
W	-57.476	-.047	.000	-53.069	-.043	.000	-54.032	-.046	.000	-53.055	-.044	.000
wspeed	8.557	.254	.000	9.222	.270	.000	7.839	.237	.000	8.496	.253	.000
w.dir	.000	.004	.695	.000	-.002	.856	.000	.004	.648	7.251E-05	.001	.943
T	30.074	3.586	.000	30.921	3.638	.000	29.019	3.543	.000	29.917	3.605	.000
q	-23.015	-2.039	.000	-23.813	-2.099	.000	-19.936	-2.131	.000	-20.699	-2.213	.000
q.rel	5.843	1.325	.000	6.010	1.339	.000	5.879	1.324	.000	6.069	1.341	.000
SVF	12.697	.131	.000	12.459	.129	.000	13.901	.147	.000	13.680	.144	.000
BSF	.002	.001	.957	.044	.023	.239	.013	.007	.715	.052	.028	.165
ISF												
PSF	.015	.008	.379	.057	.029	.016	.023	.012	.192	.066	.034	.006
GSF				-.050	-.030	.006				-.050	-.031	.005
HRE	.106	.046	.176	.135	.058	.087	.099	.044	.190	.120	.053	.114
FAR	-.128	-.025	.515	-.205	-.040	.297	-.105	-.021	.582	-.158	-.032	.406
constant	-8808.66		.000	-9063.859		.000	-8561.288		.000	-8834.073		.000
R^2	0.736			0.736			0.741			0.740		
Adjusted R^2	0.736			0.735			0.741			0.739		
F static	1111.455			1027.452			1140.602			1049.468		
No. of cases	5184			5184			5184			5184		

Table 17 - Stepwise Regression results of the overall MRT

Description/variables	Case1			Case2			Case3			Case4		
	Coefficients		Sig. level	Coefficients		Sig. level	Coefficients		Sig. level	Coefficients		Sig. level
	B	Beta		B	Beta		B	Beta		B	Beta	
U												
V	8.061	.256	.000	8.711	.273	.000	7.366	.238	.000	7.907	.252	.000
W	-57.927	-.048	.000	-57.440	-.046	.000	-54.921	-.046	.000	-55.749	-.046	.000
wSpeed	7.884	.234	.000	8.618	.252	.000	7.074	.214	.000	7.625	.227	.000
w.dir												
T	29.836	3.558	.000	30.810	3.625	.000	28.780	3.514	.000	29.767	3.587	.000
q	-22.786	-2.018	.000	-23.700	-2.089	.000	-19.727	-2.109	.000	-20.555	-2.197	.000
q.rel	5.780	1.311	.000	5.984	1.334	.000	5.814	1.309	.000	6.042	1.335	.000
SVF	13.467	.139	.000	12.358	.127	.000	14.233	.150	.000	14.336	.151	.000
BSF												
ISF												
PSF				.046	.023	.016						
GSF				-.045	-.027	.006						
HRE	.072	.031	.005	.055	.024	.034	.067	.029	.007	.067	.030	.007
FAR												
constant	-8736.378		.000	-9028.333		.000	-8486.747		.000	-8786.837		.000
R^2	0.736			0.736			0.741			0.739		
Adjusted R^2	0.736			0.735			0.741			0.739		
F static	1806.139			1438.720			1853.581			1833.507		
No. of cases	5184			5184			5184			5184		

The overall adjusted R^2 values of the models remain as generated in the multiple regression models. The R^2 too remains the same except in Case4 where it is lower in the stepwise regression analysis. Therefore, it can be seen that the ability for the variables to explain changes in MRT remains relevant in changing background conditions.

There is a clear pattern of significant variables for all cases. v, w, wSpeed, T, q, q.rel, SVF and HRE are common to all cases. The variables PSF and GSF become significant only in Case2, showing that they no longer impact MRT in a globally warmed background.

With a focus on the morphology variables, the Sky View Factor (SVF) and Height of Roughness Elements (HRE) are highlighted as the key variables that can explain the MRT change. Thus, can be utilised as key contributing variables to control the negative effects of global warming, UHI and thermal comfort.

4.1.2 Morphology variables in relation to the time of day

The following analysis series explore the three distinct zones seen in the MRT change during a particular day. That is Day, Night and that of the peak period. The objective is to investigate a possible correlation change to that of the total day. Day is defined as 06.00hrs. to 18.00hrs.

Day

Table 18 shows the comparative correlation of MRT for each climate background case. The data used for the analysis encompass all sites, models and receptor points, for the hours of the day between 06.00hrs. to 18.00hrs.

As with the total day series discussed above, for most of the variables, the correlation coefficient is weak. The morphology variables in particular have 'no or negligible relationship ' to MRT.

- Very strong relationships seen in - T
- Strong relationship is seen in - relative humidity (q.rel), Specific humidity (q)

Table 18: Total case day- Correlation of Variables to Mean Radiant Temperature

case		u	v	w	wSpeed	wDir	T	q	q.rel	SVF	BSF	ISF	PSF	GSF	HRE	FAR
case1 day	Correlation	-.040*	-084**	.019	.080**	-.023	.745**	.567**	-618**	.245**	-123**	.123**	-.029	.b	-171**	-.210**
	Significance	.018	.000	.157	.000	.108	0.000	.000	.000	.000	.000	.000	.059		.000	.000
case2 day	Correlation	-.043*	-085**	.012	.082**	-.020	.744**	.564**	-614**	.245**	-125**	.125**	-.030	-084**	-171**	-.210**
	Significance	.011	.000	.264	.000	.148	0.000	.000	.000	.000	.000	.000	.057	.000	.000	.000
case3 day	Correlation	-.040*	-091**	.023	.087**	-.025	.751**	.558**	-578**	.257**	-133**	.132**	-.031	.b	-180**	-.221**
	Significance	.018	.000	.108	.000	.096	0.000	.000	.000	.000	.000	.000	.051		.000	.000
case4 day	Correlation	-044**	-093**	.019	.089**	-.019	.748**	.555**	-569**	.258**	-134**	.133**	-.031*	-091**	-179**	-.221**
	Significance	.010	.000	.156	.000	.155	0.000	.000	.000	.000	.000	.000	.048	.000	.000	.000

**. Correlation is significant at the 0.01 level (1-tailed).

*. Correlation is significant at the 0.05 level (1-tailed).

In relation to the total case, the correlation of 'q' has weakened. As seen in the total case, variable correlations increase slightly for the global warming cases over the existing climate cases. Correlations remain the similar for green cases.

A significant increase in correlation to MRT is seen in Height of Roughness Elements (HRE) and Floor Area Ratio (FAR). This is to be expected with the increased ability of the urban fabric to create shade during the day time hours of the day.

Statistical Significance -
Most variables are seen as statistically significant, with p-value < 0.001 for most morphology variables considered. The variables w, wDir, PSF are not statistically significant. Thus, highlighting that variables that govern shading takes precedence over wind direction and nature of the natural surface.

Discussion
As seen in the total day case series, overall, the variables that could be controlled by urban design, have an impact on the correlation with MRT intensity in the microclimate.

A **stepwise regression** run for the 'day' time hours indicate a similar pattern of key variables as seen in the 'total' case. The v, w, wSpeed, T, q, q.rel and SVF remain significant. (Table 19)

The HRE that was significant for all models in the 'total' case series becomes significant for the global warming background cases only. The BSF that did not occur in the previous models become significant for the existing condition cases (case1 and case2). Similarly, PSF becomes significant only in case3. Of the morphology variables, the only variable that is significant throughout the cases is SVF, signifying SVF as the key variable for MRT control in the 'day' time hours.

Overall, the R^2 values of the regression models reduce considerably in comparison to the 'total' cases, by over 5% in all cases, signifying other variables not considered in the model are deemed to have an effect.

Table 19 - Stepwise Regression results of the overall MRT – ‘Day’

Description/variables	Case1			Case2			Case3			Case4		
	Coefficients		Sig. level	Coefficients		Sig. level	Coefficients		Sig. level	Coefficients		Sig. level
	B	Beta		B	Beta		B	Beta		B	Beta	
U												
V	12.120	.419	.000	13.015	.442	.000	11.936	.416	.000	12.457	.427	.000
W	-70.765	-.065	.000	-68.824	-.061	.000	-70.148	-.065	.000	-70.771	-.064	.000
wSpeed	10.440	.337	.000	11.433	.364	.000	11.055	.360	.000	11.336	.364	.000
w.dir												
T	33.094	4.379	.000	34.190	4.464	.000	27.956	3.778	.000	28.791	3.842	.000
q	-28.022	-2.841	.000	-29.071	-2.934	.000	-20.792	-2.522	.000	-21.517	-2.610	.000
q.rel	6.861	1.715	.000	7.107	1.748	.000	5.703	1.436	.000	5.888	1.456	.000
SVF	17.782	.200	.000	18.112	.204	.000	21.230	.243	.000	21.862	.250	.000
BSF	-.069	-.040	.009	-.061	-.035	.021						
ISF												
PSF							.047	.026	.031			
GSF												
HRE							.078	.037	.034	.082	.039	.024
FAR												
constant	-9697.710		.000	-10028.417		.000	-8208.497		.000	-8459.901		.000
R^2	0.638			0.638			0.647			0.646		
Adjusted R^2	0.637			0.637			0.646			0.645		
F static	617.189			617.229			569.645			638.788		
No. of cases	2808			2808			2808			2808		

Night

The analysis explores the correlation of MRT for the nighttime hours between 0.00hrs to 6.00hrs. and 18.00hrs. to 0.00hrs. The objective is to investigate the effect on the microclimate when there is no direct exposure to the Sun. (Table 20)

Correlation Analysis-

Correlations with MRT for the variables considered differ significantly in relation to the 'total' and 'day' cases, where, variables that can be controlled by urban design show distinct strengthening of the relationship.

- Very strong relationships seen in - SVF (for case3 and 4 only)
- Strong relationships seen in - T, q, SVF (2 and 3), HRE (3 and 4), FAR
- Moderate relationships seen in - BSF, ISF

The 'green' cases differ in their correlation to MRT. This trend was not seen in the 'total' and 'day' cases. For most variables, the coefficient of correlation increases.

There seems to be an overall pattern where, the variables that had strong correlations have reduced, while, those that were weak are now strong.

- Increase in correlation - FAR, HRE, ISF, BSF, SVF, wSpeed, v
- Reduction in correlation- q, T, wDir, w,

Statistical Significance -

As with the other series considered, most variables are seen as statistically significant, with p-value < 0.001 for most morphology variables considered. The Pervious Surface Fraction (PSF) becomes significant, where it was not for 'total' and 'day' cases. The variables u, q.rel (case4) are not statistically significant.

Discussion

The morphology variables have better coefficients of correlation at 'night'. Yet, morphology is used primarily as a strategy to ameliorate daytime heat gain. To clarify, Fig. 54 plots the effect of SVF on the MRT of the urban outdoors.

The correlation of the data analysed show that the correlation within comparative cases increase from total, to day, to night, to 1pm.

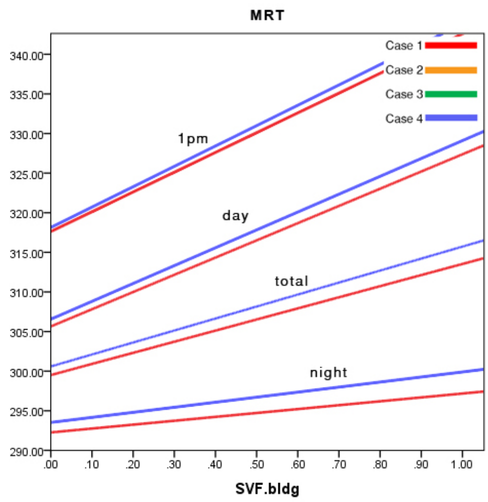


Fig. 54 - All cases - time of day comparison

SVF to MRT relationship

Here it is clearly seen that the SVF is most effective at reducing MRT at 1pm, while it is least effective at night.

It is important to note that the correlation coefficient between SVF and MRT for nighttime, remains positive. As opposed to a negative relationship that would promote nighttime radiation loss recommended in most studies. The reason for the anomaly in this study may lie in the identified over prediction of nighttime values by the ENVI-met simulation model. Literature cites this is due to the limitation in the model that ‘buildings lack thermal mass’.

4.1.3 Predicting the relationship between MRT and urban design variables for 'night-time’ hours

The objective is to generalise the variables in relation to MRT. The process adopts a stepwise regression used in the previous sections. (Table 21)

A stepwise regression run for the nighttime hours indicate a differing pattern to that of the 'total' and 'day' cases, as it is seen in the bivariate correlation discussed above. (Table 20)

Table 20 - Total case 'night'- Correlation of Variables to Mean Radiant Temperature

case		u	v	w	wSpeed	wDir	T	q	q.rel	SVF	BSF	ISF	PSF	GSF	HRE	FAR
case1 night	Correlation	-.029	-.202**	.069**	.183**	-.050**	.538**	.579**	-.012	.589**	-.316**	.311**	-.069**	.[a]	-.391**	-.491**
	Significance	.081	.000	.000	.000	.008	.000	.000	.276	.000	.000	.000	.000		.000	.000
case2 night	Correlation	-.033	-.204**	.060**	.186**	-.053**	.539**	.572**	-.016	.593**	-.320**	.311**	-.066**	-.204**	-.393**	-.494**
	Significance	.056	.000	.002	.000	.005	.000	.000	.224	.000	.000	.000	.001	.000	.000	.000
case3 night	Correlation	-.028	-.262**	.059**	.238**	-.042*	.430**	.436**	-.028	.704**	-.383**	.367**	-.072**	.[c]	-.475**	-.595**
	Significance	.085	.000	.002	.000	.020	.000	.000	.085	0.000	.000	.000	.000		.000	.000
case4 night	Correlation	-.033	-.264**	.051**	.241**	-.040*	.434**	.426**	-..037*	.708**	-.386**	.368**	-.069**	-.241**	-.476**	-.597**
	Significance	.054	.000	.007	.000	.025	.000	.000	.034	0.000	.000	.000	.000	.000	.000	.000

**. Correlation is significant at the 0.01 level (1-tailed).

*. Correlation is significant at the 0.05 level (1-tailed).

Table 21 - Stepwise Regression results of MRT - 'night'

Description/variables	Case1			Case2			Case3			Case4		
	Coefficients		Sig. level	Coefficients		Sig. level	Coefficients		Sig. level	Coefficients		Sig. level
	B	Beta		B	Beta		B	Beta		B	Beta	
U												
V	.520	.193	.000	.537	.197	.000	.593	.203	.000	.605	.204	.000
W												
wspeed												
w.dir	-.001	-.063	.000	-.001	-.059	.000	-.001	-.066	.000	-.001	-.062	.000
T	1.850	.848	0.000	1.857	.840	0.000	1.708	.707	0.000	.968	.396	.000
q										.696	.277	.000
q.rel	.224	.461	.000	.227	.463	.000	.191	.376	.000			
SVF	5.124	.615	.000	5.144	.619	.000	6.463	.717	.000	6.480	.720	.000
BSF												
ISF	.028	.212	.000	.028	.210	.000	.034	.234	.000	.033	.233	.000
PSF												
GSF												
HRE	.010	.049	.000	.010	.050	.000	.008	.039	.007	.009	.042	.003
FAR												
constant	-281.933		.000	-284.474		.000	-238.965		.000	-13.872		.056
R^2	0.823			0.821			0.815			0.813		
Adjusted R^2	0.823			0.821			0.815			0.813		
F static	1576.604			1552.072			1493.004			1472.962		
No. of cases	2376			2376			2376			2376		

Here only v, T, SVF and HRE of the key variables as seen in the 'total' case remains related. The relationship of Specific humidity (q) and relative humidity (q.rel), for case4 differs to that of the other cases, where q.rel drops off and is replaced by q as the relative variable. Impervious Surface Fraction (ISF) and Wind direction (wDir) which was removed during stepwise regression analysis of the 'total' and 'day' cases becomes significant in explaining the variation of MRT in the 'night'. The morphology variables SVF, HRE and ISF are identified as significant to the relationship.

Overall, the R^2 values of the regression models are strongest for the 'night' analyses. The ability of the variables to explain the MRT change reduces for the global warming cases in comparison to the existing background cases.

4.1.4 Predicting the MRT in relation to the urban morphology variables for the peak hour of the day

The analysis is further focused on the peak hour of the day. (Table 22) The peak hour is taken as 13.00hrs. The criterion for selection is based on the evaluation of the total day regression plots (Fig. 53), where the particular time of day shows the greatest MRT intensity.

As seen in the Table 23 (for case3), the correlation of MRT to the variables considered are stronger than the other time intervals considered, especially the variables that can be controlled by urban design. In comparison, the influences of the climatic variables decrease in correlation.

- Very strong correlation is seen in; SVF and FAR.
- Strong correlation (negative or positive) is seen in v, wind speed, T, BSF, ISF and HRE.

Other variables with a weaker correlation are excluded. It is noted that, unlike the 'night' case analysis, surface cover fraction characteristic variables are significant.

Table 22 - Total case 1pm-- Correlation of Variables to Mean Radiant Temperature

case		u	v	w	wSpeed	wDir	T	q	q.rel	SVF	BSF	ISF	PSF	GSF	HRE	FAR
case1 1pm	Correlation	-.092	-.469**	.004	.474**	.032	.483**	.224**	-.355**	.866**	-.455**	.518**	-.190**	.[a]	-.545**	-.712**
	Significance	.090	.000	.476	.000	.319	.000	.000	.000	.000	.000	.000	.003		.000	.000
case2 1pm	Correlation	-.103	-.470**	-.002	.477**	.035	.468**	.213**	-.347**	.864**	-.460**	.521**	-.190**	-.338**	-.540**	-.709**
	Significance	.066	.000	.487	.000	.304	.000	.001	.000	.000	.000	.000	.003	.000	.000	.000
case3 1pm	Correlation	-.092	-.475**	.020	.480**	.039	.490**	.219**	-.347**	.873**	-.481**	.540**	-.191**	.[a]	-.553**	-.727**
	Significance	.090	.000	.385	.000	.286	.000	.001	.000	.000	.000	.000	.002		.000	.000
case4 1pm	Correlation	-.102	-.476**	.012	.481**	.045	.474**	.210**	-.338**	.870**	-.481**	.542**	-.193**	-.351**	-.551**	-.726**
	Significance	.067	.000	.431	.000	.257	.000	.001	.000	.000	.000	.000	.002	.000	.000	.000

**. Correlation is significant at the 0.01 level (1-tailed).

*. Correlation is significant at the 0.05 level (1-tailed).

Table 23 - case3 time- Correlation of Variables to Mean Radiant Temperature

case		u	v	w	wSpeed	wDir	T	q	q.rel	SVF	BSF	ISF	PSF	GSF	HRE	FAR
case3	Correlation	-.021	-.050**	.041**	.044**	-.018	.844**	.730**	-.536**	.159**	-.083**	.082**	-.019	.[a]	-.111**	-.136**
	Significance	.063	.000	.002	.001	.094	0.000	0.000	0.000	.000	.000	.000	.087		.000	.000
case3 day	Correlation	-.040*	-.091**	.023	.087**	-.025	.751**	.558**	-.578**	.257**	-.133**	.132**	-.031	.[b]	-.180**	-.221**
	Significance	.018	.000	.108	.000	.096	0.000	.000	.000	.000	.000	.000	.051		.000	.000
case3 night	Correlation	-.028	-.262**	.059**	.238**	-.042*	.430**	.436**	-.028	.704**	-.383**	.367**	-.072**	.[c]	-.475**	-.595**
	Significance	.085	.000	.002	.000	.020	.000	.000	.085	0.000	.000	.000	.000		.000	.000
case3 1pm	Correlation	-.092	-.475**	.020	.480**	.039	.490**	.219**	-.347**	.873**	-.481**	.540**	-.191**	.[a]	-.553**	-.727**
	Significance	.090	.000	.385	.000	.286	.000	.001	.000	.000	.000	.000	.002		.000	.000

**. Correlation is significant at the 0.01 level (1-tailed).

*. Correlation is significant at the 0.05 level (1-tailed).

Stepwise Regression analysis encompassing the above is shown in Table 24;

The variables that explain the behaviour of MRT at 13.00 hrs. are limited to v, wSpeed, SVF, BSF and PSF. The adjusted coefficient of determination for these cases varying from 79.8% for case1 to 80.8% for case3.

Discussion

It is interesting to note that only **v** [Wind speed v-component (south to north)] and SVF remain relevant for all models considered.

4.2 Site Case series

The objective of the analysis series is to ascertain the effect of the variables when the measurement sites change. The sites, as mentioned in the research design (3.2.3), were chosen as a cross section across major roads. The sites vary according to the distance from the sea.

The analysis adopts a case wise approach, in keeping with the primary objective of exploring the effect that the morphology variables on MRT, for changing background climate scenarios.

<u>All sites - (under case1 background conditions) (Table 25)</u>

Correlation Analysis-

Following the pattern of the total case series, most correlation coefficients are weak.

- Very strong relationships seen in - T, q
- Strong relationships in q.rel. Except for site1, where it is 'very strong negative', but, only strong for the other sites.

The correlation weakens as s1, s3, s2, s4.

There are significant changes in correlation between sites. In addition, a definite pattern of change is not evident in relation to the distance from the sea. Yet, the correlation between variables for site1 (the site closest to the sea) is distinct in comparison.

Table 24 - Stepwise Regression results of MRT - '1pm'

Description/variables	Case1			Case2			Case3			Case4		
	Coefficients		Sig. level	Coefficients		Sig. level	Coefficients		Sig. level	Coefficients		Sig. level
	B	Beta		B	Beta		B	Beta		B	Beta	
U												
V	5.068	.535	.000	5.597	.576	.000	4.928	.504	.000	5.491	.547	.000
W												
wspeed	4.182	.414	.005	4.746	.458	.003	3.963	.379	.006	4.566	.426	.004
w.dir												
T												
q												
q.rel												
SVF	24.791	.868	.000	24.763	.861	.000	25.324	.865	.000	25.418	.860	.000
BSF	-.078	-.140	.002	-.082	-.146	.001	-.087	-.152	.001	-.088	-.152	.001
ISF												
PSF	-.126	-.216	.000	-.127	-.217	.000	-.131	-.219	.000	-.133	-.220	.000
GSF												
HRE												
FAR												
constant	325.966		.000	326.100		.000	327.558		.000	327.525		.000
R^2	0.803			0.800			0.812			0.809		
Adjusted R^2	0.798			0.795			0.808			0.804		
F static	170.732			167.508			181.377			177.441		
No. of cases	216			216			216			216		

Table 25 - case1 site series- Correlation of Variables to Mean Radiant Temperature

case1		u	v	w	wSpeed	wDir	T	q	q.rel	SVF	BSF	ISF	PSF	GSF	HRE	FAR
site1	Correlation	-.047*	-.022	.168**	.020	.004	.859**	.774**	-.755**	.110**	-.061*	.037	.010	.[a]	-.077**	-.097**
	Significance	.047	.217	.000	.235	.447	0.000	.000	.000	.000	.015	.090	.355		.003	.000
site2	Correlation	-.053*	-.049*	-.022	.050*	.003	.829**	.724**	-.593**	.162**	-.088**	.102**	-.061*	.[a]	-.097**	-.123**
	Significance	.027	.039	.211	.035	.456	0.000	.000	.000	.000	.001	.000	.014		.000	.000
site3	Correlation	-.024	-.034	.010	.031	-.055*	.851**	.722**	-.645**	.148**	-.081**	.066**	.017	.[a]	-.111**	-.130**
	Significance	.193	.110	.364	.131	.024	0.000	.000	.000	.000	.002	.009	.268		.000	.000
site4	Correlation	.000	-.056*	-.015	.027	-.036	.842**	.712**	-.553**	.142**	-.063*	.072**	-.042	.[a]	-.113**	-.127**
	Significance	.499	.022	.290	.165	.097	0.000	.000	.000	.000	.012	.005	.067		.000	.000

**. Correlation is significant at the 0.01 level (1-tailed).

*. Correlation is significant at the 0.05 level (1-tailed).

Table 26 - case2 site series- Correlation of Variables to Mean Radiant Temperature

case2		u	v	w	wSpeed	wDir	T	q	q.rel	SVF	BSF	ISF	PSF	GSF	HRE	FAR
site1	Correlation	-.052*	-.020	.173**	.019	-.005	.859**	.773**	-.754**	.111**	-.062*	.038	.011	-.060*	-.076**	-.098**
	Significance	.030	.236	.000	.251	.424	0.000	.000	.000	.000	.012	.085	.346	.016	.003	.000
site2	Correlation	-.055*	-.051*	-.030	.052*	.010	.830**	.722**	-.591**	.163**	-.089**	.103**	-.062*	-.062*	-.096**	-.123**
	Significance	.025	.034	.143	.030	.361	0.000	.000	.000	.000	.001	.000	.013	.013	.000	.000
site3	Correlation	-.028	-.036	.001	.034	-.043	.850**	.720**	-.632**	.148**	-.081**	.066**	.017	.017	-.111**	-.131**
	Significance	.155	.095	.488	.108	.063	0.000	.000	.000	.000	.002	.009	.265	.265	.000	.000
site4	Correlation	.000	-.060*	-.020	.031	-.034	.840**	.711**	-.540**	.142**	-.063*	.072**	-.042	-.042	-.113**	-.127**
	Significance	.495	.015	.240	.132	.112	0.000	.000	.000	.000	.012	.005	.066	.066	.000	.000

**. Correlation is significant at the 0.01 level (1-tailed).

*. Correlation is significant at the 0.05 level (1-tailed).

Statistical Significance -

- Most variables are seen as statistically significant, with p-value < 0.001, including most morphology variables considered.
- PSF is significant for site2 only.
- Other variables become significant for differing sites.

Thus, as in the comparison of correlation coefficients, there is no set pattern of change for differing sites.

Considering MRT change for individual sites, the interpolated lines for all sites show site1 as the warmer site with the site2 the cooler. site3 and site4 show a similar trend to site1 between 09.00hrs. to 11.00hrs. MRT for all sites vary similarly for the night and morning hours. (Fig. 55)

Variables - (Fig. 56, 57, 58, 59, 60)

Analyses of the variables show that site1 shows minimal effect on MRT in relation to the variable change. site2 shows the greatest change for most variables. site3 and site4 show similar characteristics to each other.

The implication of this is that variable to MRT relationship is effected by the geographical placement of the urban plot.

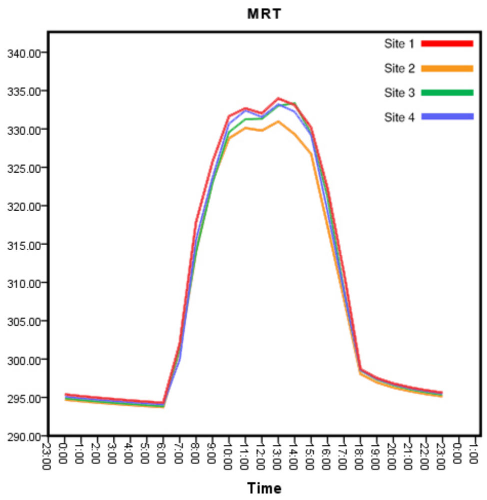


Fig. 55 - case1—site series - MRT to Time relationship

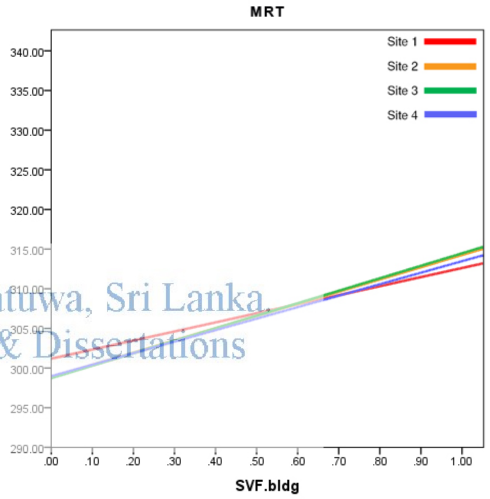


Fig. 56 - case1—site series - MRT to SVF relationship

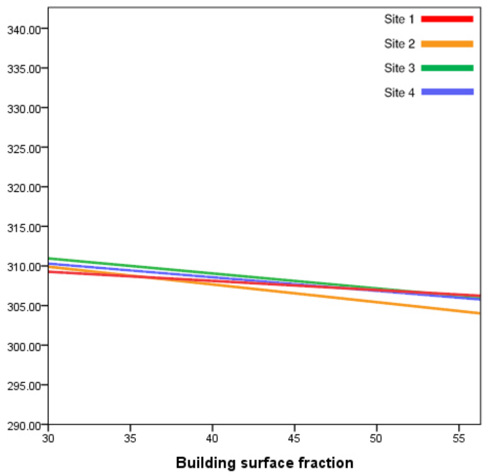


Fig. 57 - case1—site series - MRT to BSF relationship

All sites - (under case2 background conditions) (Table 26)

Correlation Analysis and statistical significance -

case2 follows a similar pattern to case1

Variables -

Correlations of variables to MRT for case2 follow a similar pattern to that of case1, for all variables considered.

All sites - (under case3 background conditions) (Table 27)

Correlation Analysis -

Most correlations are weak.

- Very strong relationships seen in - T, q,
- Strong relationships seen in - q.rel.

The correlation weakens as site1, site3, site2, site4.

In comparison of the correlation coefficient between cases (case1 & 2 to case3 & 4) show that it increases for all variables, except in q.rel, where it reduces. Yet, the correlations remain strong and significant.

Statistical Significance -

As in the previous cases, a specific pattern of change for variables is not evident. Differing variables become significant for different sites.

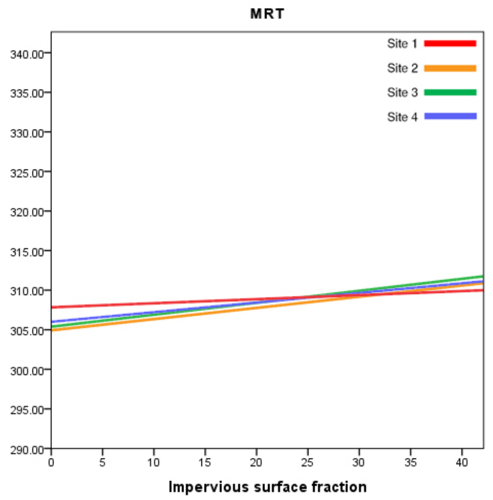


Fig. 58 - case1—site series - MRT to ISF relationship

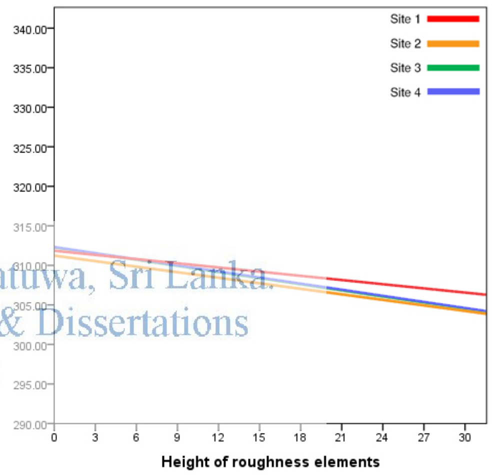


Fig. 59 - case1—site series - MRT to HRE relationship

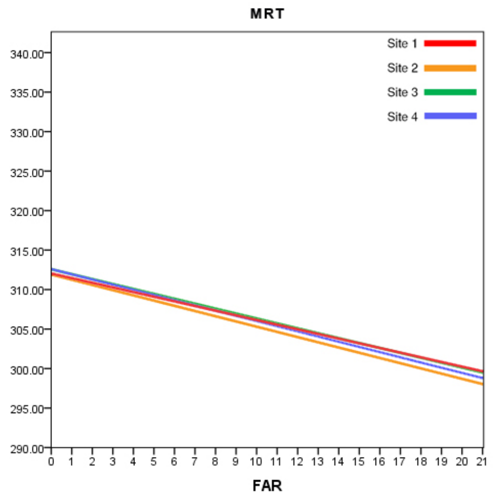


Fig. 60 - case1—site series - MRT to FAR relationship

Table 27 - case3 site series- Correlation of Variables to Mean Radiant Temperature

case3		u	v	w	wSpeed	wDir	T	q	q.rel	SVF	BSF	ISF	PSF	GSF	HRE	FAR
site1	Correlation	-.050*	-.027	.174**	.025	-.005	.861**	.777**	-.699**	.123**	-.076**	.049*	.009	.[a]	-.086**	-.113**
	Significance	.035	.168	.000	.182	.429	0.000	.000	.000	.000	.003	.038	.370		.001	.000
site2	Correlation	-.052*	-.053*	-.021	.054*	.005	.830**	.724**	-.507**	.178**	-.098**	.110**	-.065**	.[a]	-.106**	-.134**
	Significance	.031	.029	.227	.027	.429	0.000	.000	.000	.000	.000	.000	.010		.000	.000
site3	Correlation	-.023	-.037	.011	.035	-.052*	.852**	.722**	-.559**	.162**	-.086**	.070**	.018	.[a]	-.121**	-.142**
	Significance	.205	.090	.343	.104	.030	0.000	.000	.000	.000	.001	.006	.254		.000	.000
site4	Correlation	.003	-.060*	-.004	.030	-.033	.844**	.709**	-.480**	.156**	-.069**	.077**	-.044	.[a]	-.123**	-.138**
	Significance	.451	.015	.446	.140	.120	0.000	.000	.000	.000	.007	.003	.057		.000	.000

**. Correlation is significant at the 0.01 level (1-tailed).

*. Correlation is significant at the 0.05 level (1-tailed).

Table 28 - case4 site series- Correlation of Variables to Mean Radiant Temperature

case4		u	v	w	wSpeed	wDir	T	q	q.rel	SVF	BSF	ISF	PSF	GSF	HRE	FAR
site1	Correlation	-.060*	-.025	.176**	.024	-.001	.860**	.776**	-.695**	.125**	-.078**	.050*	.010	-.072**	-.086**	-.114**
	Significance	.016	.186	.000	.197	.491	0.000	.000	.000	.000	.002	.035	.361	.005	.001	.000
site2	Correlation	-.052*	-.054*	-.025	.055*	.011	.830**	.722**	-.498**	.178**	-.098**	.111**	-.066**	-.066**	-.105**	-.134**
	Significance	.031	.025	.186	.024	.350	0.000	.000	.000	.000	.000	.000	.009	.009	.000	.000
site3	Correlation	-.027	-.040	.011	.038	-.044	.850**	.720**	-.540**	.162**	-.086**	.070**	.019	.019	-.121**	-.142**
	Significance	.164	.073	.351	.083	.057	0.000	.000	.000	.000	.001	.006	.251	.251	.000	.000
site4	Correlation	.003	-.063*	-.007	.032	-.027	.841**	.707**	-.460**	.156**	-.069**	.078**	-.044	-.044	-.123**	-.138**
	Significance	.453	.012	.402	.122	.167	0.000	.000	.000	.000	.006	.003	.057	.057	.000	.000

**. Correlation is significant at the 0.01 level (1-tailed).

*. Correlation is significant at the 0.05 level (1-tailed).

MRT change for individual sites-

The overall MRT change for case3 (Fig. 61), during the day follows a similar pattern as the existing background (case1) condition. The intensity difference in background temperature of the 'global warming' cases is seen clearly. Here too, as in case1, site1 is the warmest and site2 is the cooler.

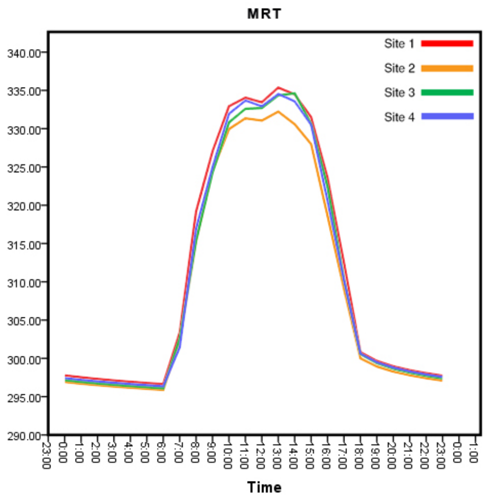


Fig. 61 - case3—site series - MRT to Time relationship

Variables -

As in case1, analyses of the variables show that site1 shows minimal effect in relation to the variable change. site2 shows the greatest change for most variables. site3 and site4 show similar characteristics. SVF to MRT relationship is taken as an example. (Fig. 62)

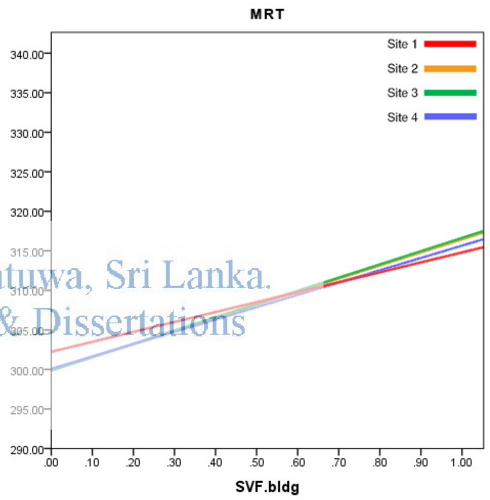


Fig. 62 - case3 - site series - SVF to MRT relationship

<u>All sites (under case4 background conditions) (Table 28)</u>

Correlation Analysis and statistical significance- case4 follows a similar pattern to case3

Variables - As with the correlation analysis, case4 follows the same pattern as case3 for all variables considered.

<u>Site1 cases compared</u>

Correlation analyses (Table 29) show there is minimal or no change between the existing, (open soil) (case1 and 3) and green surface cases (case2 and 4). This is found true for both the existing and global warming background cases. All variables show an increase in correlation with MRT when the cases change from the existing to global warming background. The effect of the global warming

Table 29 - site1 cases- Correlation of Variables to Mean Radiant Temperature

site1		u	v	w	wSpeed	wDir	T	q	q.rel	SVF	BSF	ISF	PSF	GSF	HRE	FAR
case1	Correlation	-.047*	-.022	.168**	.020	.004	.859**	.774**	-.755**	.110**	-.061*	.037	.010	.[a]	-.077**	-.097**
	Significance	.047	.217	.000	.235	.447	0.000	.000	.000	.000	.015	.090	.355		.003	.000
case2	Correlation	-.052*	-.020	.173**	.019	-.005	.859**	.773**	-.754**	.111**	-.062*	.038	.011	-.060*	-.076**	-.098**
	Significance	.030	.236	.000	.251	.424	0.000	.000	.000	.000	.012	.085	.346	.016	.003	.000
case3	Correlation	-.050*	-.027	.174**	.025	-.005	.861**	.777**	-.699**	.123**	-.076**	.049*	.009	.[a]	-.086**	-.113**
	Significance	.035	.168	.000	.182	.429	0.000	.000	.000	.000	.003	.038	.370		.001	.000
case4	Correlation	-.060*	-.025	.176**	.024	-.001	.860**	.776**	-.695**	.125**	-.078**	.050*	.010	-.072**	-.086**	-.114**
	Significance	.016	.186	.000	.197	.491	0.000	.000	.000	.000	.002	.035	.361	.005	.001	.000

**. Correlation is significant at the 0.01 level (1-tailed).

*. Correlation is significant at the 0.05 level (1-tailed).

Table 30 - site2 cases- Correlation of Variables to Mean Radiant Temperature

site2		u	v	w	wSpeed	wDir	T	q	q.rel	SVF	BSF	ISF	PSF	GSF	HRE	FAR
case1	Correlation	-.053*	-.049*	-.022	.050*	.003	.829**	.724**	-.593**	.162**	-.088**	.102**	-.061*	.[a]	-.097**	-.123**
	Significance	.027	.039	.211	.035	.456	0.000	.000	.000	.000	.001	.000	.014		.000	.000
case2	Correlation	-.055*	-.051*	-.030	.052*	.010	.830**	.722**	-.591**	.163**	-.089**	.103**	-.062*	-.062*	-.096**	-.123**
	Significance	.025	.034	.143	.030	.361	0.000	.000	.000	.000	.001	.000	.013	.013	.000	.000
case3	Correlation	-.052*	-.053*	-.021	.054*	.005	.830**	.724**	-.507**	.178**	-.098**	.110**	-.065**	.[a]	-.106**	-.134**
	Significance	.031	.029	.227	.027	.429	0.000	.000	.000	.000	.000	.000	.010		.000	.000
case4	Correlation	-.052*	-.054*	-.025	.055*	.011	.830**	.722**	-.498**	.178**	-.098**	.111**	-.066**	-.066**	-.105**	-.134**
	Significance	.031	.025	.186	.024	.350	0.000	.000	.000	.000	.000	.000	.009	.009	.000	.000

**. Correlation is significant at the 0.01 level (1-tailed).

*. Correlation is significant at the 0.05 level (1-tailed).

background change is seen in the peak daytime and the nighttime hours only (Fig. 63). Comparison of variables across cases shows an increase in the rate of change in relation to MRT. Where the relationship is positive, the rate of change between cases widened (Fig. 64), while, where the relationship is negative the rate of change narrowed (Fig. 65). This is seen especially in the FAR to MRT relationship.

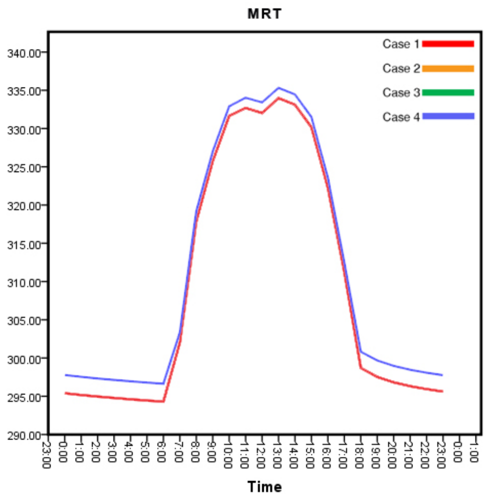


Fig. 63 - site1 cases - MRT to Time relationship

<u>Site2 cases compared</u>

As with the site1 cases there is minimal or no change between the open soil and green surface cases for both the existing and global warming background cases. For all variables considered, the correlation between existing to global warming cases increase. (Table 30). PSF, which was not significant in the other sites become significant for site2.

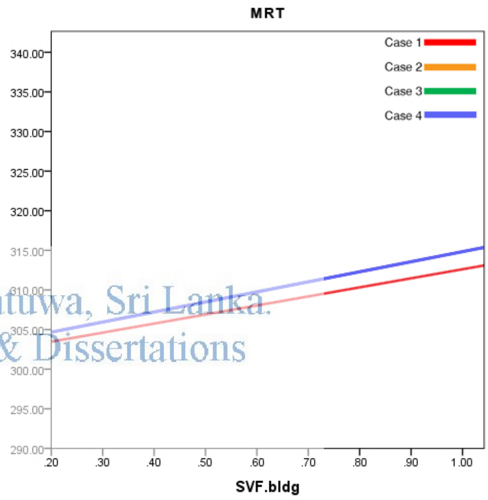


Fig. 64 - site1 cases - SVF to MRT relationship

<u>Site3 cases and Site4 cases</u>

The analysis of background cases within individual sites yield similar correlation patterns to each other. (Table 31 and Table 32)

Correlation Analysis -

Most correlations are weak.

- Very strong relationships seen in - T, q
- Strong relationships seen in - q.rel

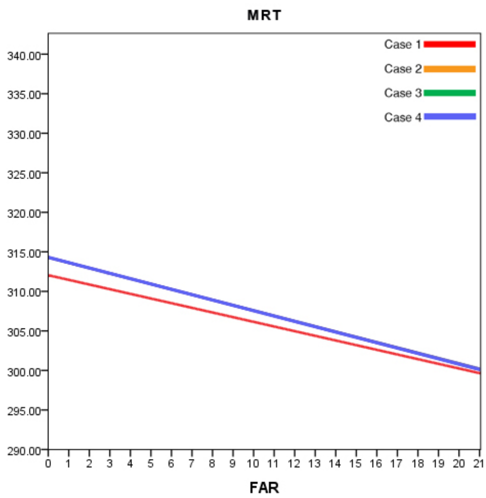


Fig. 65 - site1 cases - FAR to MRT relationship

Table 31 - site3 cases- Correlation of Variables to Mean Radiant Temperature

site3		u	v	w	wSpeed	wDir	T	q	q.rel	SVF	BSF	ISF	PSF	GSF	HRE	FAR
case1	Correlation	-.024	-.034	.010	.031	-.055*	.851**	.722**	-.645**	.148**	-.081**	.066**	.017	.[a]	-.111**	-.130**
	Significance	.193	.110	.364	.131	.024	0.000	.000	.000	.000	.002	.009	.268		.000	.000
case2	Correlation	-.028	-.036	.001	.034	-.043	.850**	.720**	-.632**	.148**	-.081**	.066**	.017	.017	-.111**	-.131**
	Significance	.155	.095	.488	.108	.063	0.000	.000	.000	.000	.002	.009	.265	.265	.000	.000
case3	Correlation	-.023	-.037	.011	.035	-.052*	.852**	.722**	-.559**	.162**	-.086**	.070**	.018	.[a]	-.121**	-.142**
	Significance	.205	.090	.343	.104	.030	0.000	.000	.000	.000	.001	.006	.254		.000	.000
case4	Correlation	-.027	-.040	.011	.038	-.044	.850**	.720**	-.540**	.162**	-.086**	.070**	.019	.019	-.121**	-.142**
	Significance	.164	.073	.351	.083	.057	0.000	.000	.000	.000	.001	.006	.251	.251	.000	.000

**. Correlation is significant at the 0.01 level (1-tailed).

*. Correlation is significant at the 0.05 level (1-tailed).

Table 32 - site4 cases- Correlation of Variables to Mean Radiant Temperature

site4		u	v	w	wSpeed	wDir	T	q	q.rel	SVF	BSF	ISF	PSF	GSF	HRE	FAR
case1	Correlation	.000	-.056*	-.015	.027	-.036	.842**	.712**	-.553**	.142**	-.063*	.072**	-.042		-.113**	-.127**
	Significance	.499	.022	.290	.165	.097	0.000	.000	.000	.000	.012	.005	.067		.000	.000
case2	Correlation	.000	-.060*	-.020	.031	-.034	.840**	.711**	-.540**	.142**	-.063*	.072**	-.042	-.042	-.113**	-.127**
	Significance	.495	.015	.240	.132	.112	0.000	.000	.000	.000	.012	.005	.066	.066	.000	.000
case3	Correlation	.003	-.060*	-.004	.030	-.033	.844**	.709**	-.480**	.156**	-.069**	.077**	-.044		-.123**	-.138**
	Significance	.451	.015	.446	.140	.120	0.000	.000	.000	.000	.007	.003	.057		.000	.000
case4	Correlation	.003	-.063*	-.007	.032	-.027	.841**	.707**	-.460**	.156**	-.069**	.078**	-.044	-.044	-.123**	-.138**
	Significance	.453	.012	.402	.122	.167	0.000	.000	.000	.000	.006	.003	.057	.057	.000	.000

**. Correlation is significant at the 0.01 level (1-tailed).

*. Correlation is significant at the 0.05 level (1-tailed).

There is none or minimal change in correlation between existing to green surface cases. Correlation increases in all other morphology variables considered. The coefficient of correlation is strongest for SVF.

Statistical Significance -

Not significant - u, v, w, wSpeed, PSF, GSF. wDir (for site4 only)

Statistical significance increase (between background conditions)- BSF, PSF (for site3 only), GSF (for site3 only)

Discussion -

Case4 (green global warming) background scenario to individual site comparison

The analysis explored in the preceding sections are summarised in Table 33, as a means to ascertaining a probable relationship of individual sites to that of the overall scenario. The table sorts the strength of the correlation between MRT and the variable, in descending order.

Table 33 : case4 (green, global warming) background scenario to individual site - correlation comparison

T	q	q.rel	SVF	BSF	ISF	PSF	GSF	HRE	FAR
site1	site1	site1	site2	site2	site2	site2	site1	site4	site3
site3	case4	site3	site3	site3	case4	site3	site2	site3	site4
case4	site2	case4	case4	case4	site4	site1	case4	case4	case4
site4	site3	site2	site4	site1	site3	case4	site3	site2	site2
site2	site4	site4	site1	site4	site1	site4	site4	site1	site1

Correlations of variables at each individual site do not show a definite pattern of variance with those of the overall case4 scenario. site1 is distinct terms of both the climatic variables and morphology variables. As with previous analysis, the warmer sites have stronger correlation to climatic variables, while the cooler sites have stronger correlation to the morphology variables. The exception seems to be in the surface characteristic variables, where the correlation to MRT is comparatively weak, with only the GSF being strong.

Table 34 shows the same summarisation for the night-time hours.

Unlike the total day case scenario, the overall scenario correlation for the climatic variables is weakest at night-time. Especially for T and q.rel. The comparative behaviour of the overall scenario with those of the individual sites, do not show a pattern for the morphology variables for the same night-time hours, as was seen in the total day scenario.

Table 34 - case4 (green, global warming) background scenario to individual site - correlation comparison - night

T	q	q.rel	SVF	BSF	ISF	PSF	GSF	HRE	FAR
site3	site1	site3	site2	site1	site4	site4	site1	site3	site3
site4	case4	site4	site3	site2	site2	site2	case4	case4	site1
site2	site3	site2	case4	case4	case4	site3	site4	site4	case4
site1	site2	site1	site1	site4	site1	case4	site2	site1	site4
case4	site4	case4	site4	site3	site3	site1	site3	site2	site2

The correlation of the morphology variables for individual sites, maintain a similar hierarchy to that of the total day. Distinct differences are seen for site1.

Discussion -

The characteristics seen in site1 have distinct differences to those of the other sites. This is seen in the relationship between MRT and morphology variables as well. It can be said that the proximity to the sea is what drives the distinct effect on the behaviour of the variables considered in site1. Though it has the advantage of the sea breeze, it is more exposed to the western sun. With a significant impervious surface (Marine Drive) along its urban block edge, makes it the warmest overall site, during the day time hours of the day.

site2, though it shows the lowest intensity of MRT, mainly for the peak hours of the day. The variation of the relationships, in particular to the morphology variables, is closer in their behaviour to that of site3 and site4.

site2 is the coolest during the day. It can be ascertained that this is due to the fact that site2 has the benefit of the sea breeze and also shading from the adjacent blocks. site3 and site4 are situated further from the sea, therefore the effect of the ocean breeze is reduced.

Comparatively the sites show minimal variation for the night-time hours.

Correlations of variables at each individual site do not show a definite pattern of variance with those of the overall case4 scenario, for both the total day and night-time periods.

4.3 Model Case series

The series analyse the behaviour of selected variables specific to morphology models defined in the research design (3.2.3). The models are compared on a case-by-case basis to ascertain the effect of the changing background condition on the variables. The objective is also to establish the best-case scenario for mitigating the negative effects of a warmer microclimate.

The models analysed are for all sites and receptor points. Therefore seeks a generalised overview of the effect of the changed morphology on the predictor variables.

<u>All models - (under case1 background conditions) (Table 35)</u>

Correlation Analysis -

Most correlations are weak.

- Very strong relationships seen in - T, Specific humidity.
- Strong relationships seen in - relative humidity

Hierarchical Change in correlation-

Table 36 explores the changing morphology with that of the correlation between the predictor variables and MRT.

The behaviour of the climatic variables shows a definite pattern. The correlation is strongest for the LCZ3 (m5) model, while it is weakest for the High edge model (m3).

Table 36: case1 models - Hierarchical Change in correlation to MRT							
Variables	Hierarchical Change in correlation to MRT (weaken from left to right)						
Climatic variables							
T	-	m5	m1	m6	m2	m4	m3
q	-	m5	m1	m6	m2	m4	m3
q.rel	-	m5	m1	m6	m2	m4	m3
Morphology variables							
SVF	-	m4	m2	m6	m1	m3	m5
BSF	-	m4	m6	m3	m2	m5	m1(not significant)
ISF	-	m2	m4	m6	m5	m3	m1(not significant)
PSF	-	not significant for all models					
HRE	-	m6	m2	not significant for other models			
FAR	-	m2	m4	m6	m1	m5	m3(not significant)

Table 35 - case1 models- Correlation of Variables to Mean Radiant Temperature

case-1		u	v	w	wSpeed	wDir	T	q	q.rel	SVF	BSF	ISF	PSF	GSF	HRE	FAR
model-1	Correlation	-.010	.004	.020	-.010	-.062*	.857**	.761**	-.674**	.091**	-.026	.037	-.021	.[a]	-.040	-.058*
	Significance	.379	.455	.276	.390	.035	.000	.000	.000	.004	.224	.137	.272		.122	.043
model-2	Correlation	-.040	-.060*	.014	.063*	-.012	.841**	.731**	-.601**	.150**	-.082**	.102**	-.046	.[a]	-.130**	-.130**
	Significance	.123	.039	.344	.031	.358	.000	.000	.000	.000	.008	.001	.088		.000	.000
model-3	Correlation	.031	-.024	.075*	.014	.026	.829**	.711**	-.566**	.089**	-.084**	.059*	.011	.[a]	.045	-.043
	Significance	.180	.239	.014	.344	.221	.000	.000	.000	.004	.007	.041	.371		.091	.103
model-4	Correlation	.012	-.051	.079**	.044	.000	.833**	.701**	-.581**	.128**	-.109**	.099**	-.012	.[a]	.[a]	-.109**
	Significance	.362	.066	.010	.096	.497	.000	.000	.000	.000	.001	.002	.363			.001
model-5	Correlation	-.048	-.030	.064*	.027	-.014	.859**	.765**	-.684**	.085**	-.059*	.071*	-.030	.[a]	.[a]	-.058*
	Significance	.080	.190	.030	.212	.344	.000	.000	.000	.006	.043	.019	.192			.044
model-6	Correlation	-.021	-.054	.079*	.045	-.014	.846**	.734**	-.620**	.110**	-.091**	.079*	-.008	.[a]	-.083**	-.101**
	Significance	.268	.056	.011	.091	.338	.000	.000	.000	.001	.004	.010	.409		.007	.002

**. Correlation is significant at the 0.01 level (1-tailed).

*. Correlation is significant at the 0.05 level (1-tailed).

Table 37 - case-2 models- Correlation of Variables to Mean Radiant Temperature

case-2		u	v	w	wSpeed	wDir	T	q	q.rel	SVF	BSF	ISF	PSF	GSF	HRE	FAR
model-1	Correlation	-.011	.002	.010	-.007	-.046	.855**	.757**	-.662**	.091**	-.026	.038	-.021	-.036	-.039	-.058*
	Significance	.374	.478	.388	.421	.087	.000	.000	.000	.004	.220	.133	.270	.146	.125	.043
model-2	Correlation	-.043	-.060*	.010	.063*	-.011	.841**	.730**	-.600**	.151**	-.083**	.102**	-.046	-.065*	-.130**	-.130**
	Significance	.105	.039	.384	.033	.375	.000	.000	.000	.000	.008	.001	.090	.028	.000	.000
model-3	Correlation	.031	-.026	.073*	.016	.026	.828**	.710**	-.556**	.089**	-.085**	.060*	.011	-.034	.047	-.043
	Significance	.182	.219	.016	.321	.219	.000	.000	.000	.004	.006	.039	.375	.159	.086	.105
model-4	Correlation	.010	-.051	.074*	.044	.006	.834**	.702**	-.583**	.130**	-.111**	.100**	-.011	-.067*	.a	-.111**
	Significance	.382	.066	.015	.096	.430	.000	.000	.000	.000	.001	.002	.369	.025		.001
model-5	Correlation	-.050	-.030	.074*	.028	-.009	.858**	.764**	-.676**	.086**	-.059*	.071*	-.030	-.047	.a	-.059*
	Significance	.069	.189	.015	.204	.393	.000	.000	.000	.006	.041	.018	.190	.083		.043
model-6	Correlation	-.024	-.054	.055	.046	-.019	.845**	.734**	-.612**	.111**	-.091**	.079**	-.008	-.055	-.084**	-.101**
	Significance	.243	.056	.052	.090	.292	.000	.000	.000	.001	.004	.010	.408	.053	.007	.001

**. Correlation is significant at the 0.01 level (1-tailed).

*. Correlation is significant at the 0.05 level (1-tailed).

Unlike the climatic variables, the morphology variables do not show a definite pattern in their correlation to MRT. Although, for many of the variables the LCZ2 (m4) and High centre (m2) models show stronger correlations. The correlation coefficient for SVF is strongest in all models.

Statistical significance -

Variables are seen as statistically significant, with p-value < 0.001 for most morphology variables considered.

Not significant -u, w, wSpeed, wDir (only m1), PSF, GSF

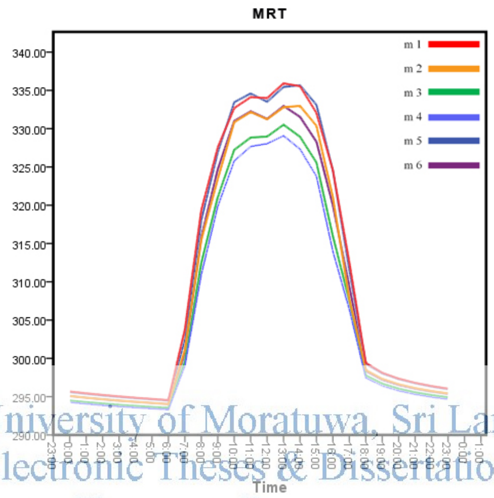


Fig. 66 - case1—model series - MRT to Time relationship

Analyses of the overall MRT change for each model during the day, show distinct differences. (Fig. 66) The warmest models are the base case (m1) and LCZ3 (m5). The coolest models are LCZ2 (m4) and the High Edge model (m4). The variation patterns between models apply for both day and night time hours, albeit at varying change of rate.

The highest differences are seen when the sun is at its peak. This is envisioned to be caused by the varying ability of the urban fabric to shade the outdoors. Even for morphology models that achieve this during the early and latter part of the day, the built fabric loses this ability when the sun directly above the street / open space, thus driving the MRT to a higher threshold.

<u>All models - (under case2 background conditions) (Table 37)</u>

Correlation Analysis -

Most correlations are weak.

- Very strong relationships seen in - T, Specific humidity
- Strong relationships seen in - relative humidity

The variables, both climatic and morphology follow a similar pattern to that of the case1 scenario. Except for specific humidity (q) where m4 shows a weaker correlation than m3.

Statistical significance -

Not significant - u , v (only m2), w (only m3,m4,m5), wSpeed (m2 only), wDir, PSF, GSF (m2 and m4 only).

The MRT change for each model during the day, show no difference to the pattern that was seen in case1. (Fig. 67)

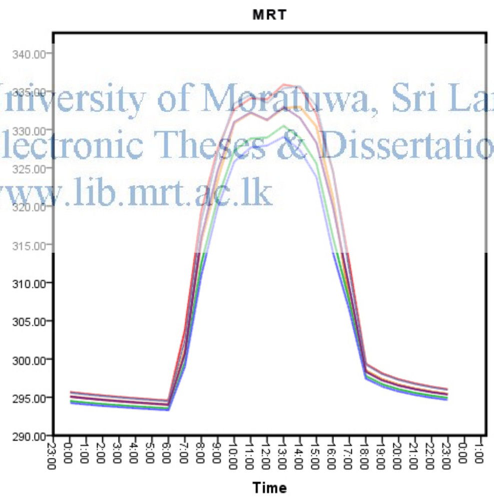


Fig. 67 - case2—model series - MRT to Time relationship

<u>All models - (under case3 background conditions) (Table 38)</u>

Correlation Analysis (Table 38) -

Most correlations are weak.

- Very strong relationships seen in - T, q
- Strong relationships seen in - q.rel

Table 38 - case3 models- Correlation of Variables to Mean Radiant Temperature

Case- 3		u	v	w	wSpeed	wDir	T	q	q.rel	SVF	BSF	ISF	PSF	GSF	HRE	FAR
model-1	Correlation	-.009	.005	.028	-.012	-.067*	.860**	.764**	-.603**	.101**	-.029	.041	-.022	.[a]	-.043	-.065*
	Significance	.397	.438	.209	.367	.024	.000	.000	.000	.002	.197	.116	.263		.101	.029
model-2	Correlation	-.036	-.067*	.025	.072*	-.002	.841**	.735**	-.520**	.164**	-.100**	.120**	-.050	.[a]	-.145**	-.148**
	Significance	.144	.025	.230	.018	.476	.000	.000	.000	.000	.002	.000	.072		.000	.000
model-3	Correlation	.034	-.027	.079*	.017	.021	.830**	.712**	-.480**	.100**	-.093**	.065*	.013	.[a]	.049	-.049
	Significance	.157	.217	.010	.312	.270	.000	.000	.000	.002	.003	.029	.354		.076	.075
model-4	Correlation	.016	-.058*	.097**	.050	.007	.833**	.701**	-.501**	.141**	-.119**	.108**	-.013	.[a]	.[a]	-.119**
	Significance	.319	.046	.002	.069	.422	.000	.000	.000	.000	.000	.001	.352			.000
model-5	Correlation	-.046	-.031	.071*	.029	-.012	.862**	.768**	-.613**	.095**	-.065*	.078*	-.032	.[a]	.[a]	-.065*
	Significance	.090	.180	.018	.195	.364	.000	.000	.000	.003	.027	.011	.175			.029
model-6	Correlation	-.021	-.061*	.078*	.052	-.014	.847**	.738**	-.538**	.123**	-.101**	.088**	-.009	.[a]	-.092**	-.112**
	Significance	.271	.035	.011	.063	.345	.000	.000	.000	.000	.002	.005	.393		.003	.000

**. Correlation is significant at the 0.01 level (1-tailed).

*. Correlation is significant at the 0.05 level (1-tailed).

Table 39 - case4 models- Correlation of Variables to Mean Radiant Temperature

case-4		u	v	w	wSpeed	wDir	T	q	q.rel	SVF	BSF	ISF	PSF	GSF	HRE	FAR
model-1	Correlation	-.011	.003	.016	-.008	-.038	.857**	.760**	-.580**	.100**	-.029	.041	-.022	-.039	-.043	-.064*
	Significance	.377	.468	.317	.409	.132	.000	.000	.000	.002	.195	.114	.260	.129	.104	.030
model-2	Correlation	-.038	-.066*	.017	.070*	-.012	.841**	.735**	-.514**	.165**	-.101**	.120**	-.049	-.082**	-.145**	-.149**
	Significance	.129	.027	.310	.020	.361	.000	.000	.000	.000	.002	.000	.073	.008	.000	.000
model-3	Correlation	.033	-.028	.087**	.018	.028	.828**	.711**	-.464**	.100**	-.093**	.066*	.012	-.037	.050	-.048
	Significance	.166	.204	.005	.302	.207	.000	.000	.000	.002	.003	.027	.360	.140	.071	.077
model-4	Correlation	.015	-.057*	.103**	.050	.011	.834**	.701**	-.501**	.143**	-.121**	.109**	-.013	-.073*	.[a]	-.121**
	Significance	.332	.047	.001	.070	.369	.000	.000	.000	.000	.000	.001	.354	.016		.000
model-5	Correlation	-.047	-.031	.083**	.029	-.006	.860**	.767**	-.597**	.096**	-.066*	.078*	-.032	-.051	.[a]	-.065*
	Significance	.085	.179	.007	.198	.430	.000	.000	.000	.002	.026	.011	.174	.066		.028
model-6	Correlation	-.025	-.061*	.062*	.052	-.015	.845**	.738**	-.523**	.124**	-.101**	.088**	-.009	-.061*	-.093**	-.113**
	Significance	.231	.036	.033	.065	.334	.000	.000	.000	.000	.001	.005	.393	.037	.003	.000

**. Correlation is significant at the 0.01 level (1-tailed).

*. Correlation is significant at the 0.05 level (1-tailed).

Statistical Significance -

Not significant - u, v (only m4), w (only m4, m6), wSpeed, wDir (m1 only), PSF, GSF

<u>All models - (under case4 background conditions) (Table 39)</u>

Correlation Analysis -

Most correlations are weak.

- Very strong relationships seen in - T, q
- Strong relationships seen in - q.rel

Statistical Significance -

Not significant - u, v (only m4), w (only m4, m6), wSpeed, wDir (m1 only), PSF, GSF

The patterns seen for both case3 and case4 follow similar patterns to those of case1 and case2. The overall behaviour of the variables in relation to the changing background conditions do differ. Although, the global warming cases show an increased correlation to MRT, the Green surface cases do not differ from the existing cases.

<u>Comparison of case1 (existing) and case4 (green global warming) for all models</u>

The analysis explores the existing background case models with those of the global warming cases. The objective of the comparison is to ascertain how the modified morphology models in a warmed context, would behave in comparison to the existing microclimate conditions.

Fig. 68. Shows the existing case (m1– case1) depicted by the black line. Analysis shows that most morphology options can reduce the overall MRT in the urban outdoors for much of the daytime hours.

The models that are warmer than the existing case are the global warming case scenario of the existing climate (m1– case4) and that of LCZ3 (m5 – case4). The model that shows the lowest MRT intensity is LCZ2 (m4 - case4).

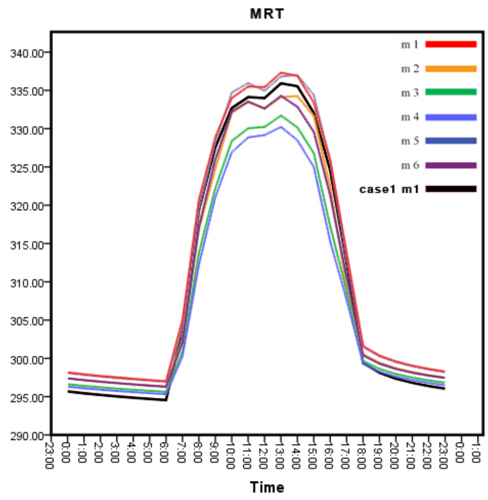


Fig. 68 - case1 (m1) to case4 (all models) comparison- MRT to Time relationship

All models are warmer at night. m5 and m3 models are nearest to the existing situation, especially for hours between 18.00hrs. to 22.00hrs. The largest variations of these models are seen between 03.00hrs. to 06.00hrs.

Discussion

Urban morphology changes can help mitigate or even roll back the negative effects caused to the microclimate by global warming. The high-density options, especially when they are at the edge of the street (m3 and m4) have a better ability to cool the outdoors.

Morphology changes do not help reduce MRT for the night-time hours as much as for the day. The cooler LCZ2 model (m4) comes closest to MRT trend shown in the existing case (case1 - m1). The green surface cases (case2 and case4) have little or no effect on the MRT, even when morphology changes.

Morphology variables show a weak correlation to MRT for all models. The strongest correlation is seen in SVF.

4.4 Receptor case series

The objective is to determine the sensitivity of the variables in relation to where the measurement point occurs, relative to an urban block.

Receptor point - a term generic to ENVI-met, denotes a measurement point in the simulation model. The simulation software generates specific data for each receptor point that is defined. As outlined in the research design, (Table 14) the analyses is approached as two parts;

- **As individual receptors**
- **As street orientation**

4.4.1 Individual receptor series

<u>All receptors- (under case1background conditions) (Table 40)</u>

Table 40 shows the receptors for the major directions together with that of the centre of the block

Correlation Analysis -

Analysis of the correlations shows a distinct difference in the receptor at the center of block (r1). The variables of r1 have the strongest correlation for SVF, HRE and FAR.

r9 - (south-west) showed the lowest correlation for SVF, ISF, HRE and FAR.

The other receptors don't show a distinct pattern in their variation.

Statistical Significance -

BSF is 'not significant' for all receptors. While ISF and PSF is only significant for r2 - (east).

Table 40 - case-1 receptors- Correlation of Variables to Mean Radiant Temperature

case-1		u	v	w	wSpeed	wDir	T	q	q.rel	SVF	BSF	ISF	PSF	GSF	HRE	FAR
receptor-1	Correlation	-.113**	-.064	-.076*	.057	-.016	.817**	.757**	-.519**	.160**	-.021	.025	.010	.[a]	-.162**	-.161**
	Significance	.003	.064	.034	.084	.350	.000	.000	.000	.000	.311	.277	.405		.000	.000
receptor-2	Correlation	-.057	-.043	.131**	.043	-.033	.857**	.758**	-.715**	.155**	-.042	.079*	-.106**	.[a]	-.088*	-.095*
	Significance	.086	.154	.001	.153	.214	.000	.000	.000	.000	.160	.029	.005		.018	.011
receptor-3	Correlation	.093*	-.074*	-.031	-.078*	-.047	.838**	.754**	-.618**	.149**	-.053	-.002	.049	.[a]	-.111**	-.121**
	Significance	.013	.038	.228	.030	.130	.000	.000	.000	.000	.102	.477	.119		.004	.002
receptor-4	Correlation	-.039	.030	.039	-.033	-.051	.902**	.774**	-.789**	.123**	-.048	-.005	.053	.[a]	-.094*	-.103**
	Significance	.178	.235	.177	.215	.112	.000	.000	.000	.002	.125	.456	.100		.012	.006
receptor-5	Correlation	-.016	-.053	-.040	.039	.030	.821**	.739**	-.645**	.113**	-.027	-.013	.035	.[a]	-.098**	-.102**
	Significance	.353	.100	.168	.172	.234	.000	.000	.000	.003	.258	.375	.202		.009	.007
receptor-6	Correlation	-.062	-.015	-.075*	.002	-.003	.871**	.787**	-.717**	.130**	-.014	.031	-.052	.[a]	-.114**	-.114**
	Significance	.069	.359	.037	.478	.476	.000	.000	.000	.001	.367	.231	.106		.003	.003
receptor-7	Correlation	-.026	.002	.036	-.017	-.004	.872**	.789**	-.764**	.117**	-.051	.039	.038	.[a]	-.091*	-.108**
	Significance	.267	.482	.193	.346	.459	.000	.000	.000	.002	.111	.174	.183		.015	.005
receptor-8	Correlation	.008	.004	.252**	-.008	-.010	.829**	.707**	-.726**	.090*	.029	.022	-.028	.[a]	-.084*	-.081*
	Significance	.424	.459	.000	.425	.402	.000	.000	.000	.015	.246	.299	.255		.022	.025
receptor-9	Correlation	-.122**	-.027	-.033	.028	-.060	.836**	.721**	-.636**	.083*	-.047	-.025	.044	.[a]	-.066	-.080*
	Significance	.002	.261	.214	.249	.074	.000	.000	.000	.023	.128	.277	.146		.057	.027

**. Correlation is significant at the 0.01 level (1-tailed).

*. Correlation is significant at the 0.05 level (1-tailed).

<u>All receptors- (under case2 background conditions) (Table 41)</u>

The case2 receptor correlation (Table 41) follows a similar pattern to that of case1.

<u>All receptors- (under case3 background conditions) (Table 42)</u>

Overall, the variables follow a similar pattern to that of case1 and case2, although the correlation increases for case3 (Table 42).

<u>All receptors- (under case4 background conditions) (Table 43)</u>

Unlike other comparison between cases analysed in the preceding sections, case4 receptor point, correlation data vary in comparison to case3. That is, the 'green' case in a global warming background condition (case4) differs to the 'open soil' case (case3), in relation to the correlation coefficient values of the variables considered. (SVF, HRE and FAR). The variables that are not significant are not included in this analysis.

The main differences are seen in r5 (south) and r6 (north-east). Changes are also seen in r7 (north-west) and r8 (south-east), but to a lesser extent than that of r5 and r6.

4.4.2 Street orientation series

The comparison analyses the receptor points in groups to ascertain the effect of the changing morphology on the microclimate of the differently oriented streets. They are simplified to north-south oriented streets, east-west oriented streets and as the

Fig. 69- Typical representation of 'streets' that bound an urban block

Table 41 - case-2 receptors- Correlation of Variables to Mean Radiant Temperature

case-2		u	v	w	wSpeed	wDir	T	q	q.rel	SVF	BSF	ISF	PSF	GSF	HRE	FAR
receptor-1	Correlation	-.105**	-.070*	-.078*	.062	-.013	.818**	.755**	-.518**	.159**	-.017	.023	.008	.008	-.160**	-.159**
	Significance	.006	.045	.031	.070	.377	.000	.000	.000	.000	.338	.291	.426	.427	.000	.000
receptor-2	Correlation	-.068	-.045	.141**	.044	-.041	.855**	.756**	-.710**	.157**	-.041	.079*	-.107**	-.107**	-.087*	-.095*
	Significance	.052	.141	.000	.143	.164	.000	.000	.000	.000	.161	.029	.005	.005	.018	.011
receptor-3	Correlation	.093*	-.075*	-.039	-.078*	-.044	.838**	.756**	-.618**	.147**	-.055	-.003	.052	.052	-.111**	-.121**
	Significance	.013	.036	.177	.031	.144	.000	.000	.000	.000	.093	.472	.108	.106	.004	.002
receptor-4	Correlation	-.043	.030	.032	-.032	-.051	.901**	.774**	-.783**	.123**	-.048	-.005	.054	.012	-.094*	-.103**
	Significance	.154	.240	.222	.224	.113	.000	.000	.000	.002	.125	.456	.100	.389	.012	.007
receptor-5	Correlation	-.018	-.053	-.029	.042	.024	.820**	.738**	-.631**	.113**	-.027	-.013	.035	.047	-.098**	-.102**
	Significance	.337	.101	.246	.159	.282	.000	.000	.000	.003	.257	.378	.204	.130	.009	.007
receptor-6	Correlation	-.065	-.014	-.067	.002	.004	.870**	.786**	-.713**	.130**	-.015	.028	-.044	-.028	-.114**	-.114**
	Significance	.059	.366	.054	.479	.461	.000	.000	.000	.001	.358	.248	.144	.254	.003	.003
receptor-7	Correlation	-.028	.002	.020	-.015	.001	.871**	.788**	-.758**	.117**	-.050	.039	.037	-.017	-.091*	-.108**
	Significance	.254	.480	.312	.357	.493	.000	.000	.000	.002	.118	.175	.190	.343	.014	.005
receptor-8	Correlation	.004	.003	.178**	-.006	-.005	.827**	.705**	-.714**	.090*	.029	.022	-.027	-.023	-.084*	-.081*
	Significance	.464	.473	.000	.442	.453	.000	.000	.000	.015	.245	.301	.257	.291	.022	.026
receptor-9	Correlation	-.120**	-.033	-.030	.035	-.045	.835**	.721**	-.634**	.085*	-.050	-.024	.045	-.035	-.067	-.082*
	Significance	.002	.213	.236	.202	.139	.000	.000	.000	.021	.117	.283	.140	.202	.055	.025

**. Correlation is significant at the 0.01 level (1-tailed).

*. Correlation is significant at the 0.05 level (1-tailed).

Table 42 - case-3 receptors - Correlation of Variables to Mean Radiant Temperature															
case-3		u	v	w	wSpeed	wDir	T	q	q.rel	SVF	BSF	ISF	PSF	GSF	HRE	FAR
receptor-1	Correlation	-.105**	-.063	-.086*	.055	-.020	.816**	.754**	-.367**	.177**	-.020	.026	.009	.[a]	-.179**	-.177**
	Significance	.006	.065	.020	.093	.317	.000	.000	.000	.000	.317	.268	.414		.000	.000
receptor-2	Correlation	-.054	-.048	.148**	.047	-.028	.859**	.758**	-.650**	.170**	-.049	.085*	-.109**	.[a]	-.096*	-.106**
	Significance	.096	.125	.000	.131	.254	.000	.000	.000	.000	.122	.021	.004		.011	.006
receptor-3	Correlation	.094*	-.070*	-.024	-.079*	-.055	.838**	.755**	-.528**	.164**	-.058	-.002	.053	.[a]	-.122**	-.132**
	Significance	.012	.046	.285	.029	.096	.000	.000	.000	.000	.081	.486	.102		.002	.001
receptor-4	Correlation	-.032	.039	.036	-.043	-.052	.904**	.776**	-.727**	.131**	-.061	.010	.049	.[a]	-.103**	-.120**
	Significance	.220	.173	.197	.153	.106	.000	.000	.000	.001	.073	.408	.118		.007	.002
receptor-5	Correlation	-.017	-.051	-.044	.039	.016	.823**	.741**	-.530**	.125**	-.050	-.012	.034	.[a]	-.108**	-.115**
	Significance	.344	.112	.144	.175	.353	.000	.000	.000	.001	.114	.388	.205		.005	.003
receptor-6	Correlation	-.061	-.009	-.071*	-.003	.000	.873**	.788**	-.652**	.141**	-.014	.029	-.043	.[a]	-.125**	-.124**
	Significance	.071	.410	.043	.476	.498	.000	.000	.000	.000	.371	.245	.152		.001	.001
receptor-7	Correlation	-.029	-.002	.052	-.011	-.001	.874**	.790**	-.706**	.130**	-.060	.049	.042	.[a]	-.099**	-.119**
	Significance	.244	.478	.108	.394	.491	.000	.000	.000	.001	.077	.122	.158		.009	.002
receptor-8	Correlation	.008	.004	.260**	-.008	-.009	.833**	.708**	-.673**	.100**	.030	.022	-.027	.[a]	-.093*	-.091*
	Significance	.426	.457	.000	.426	.414	.000	.000	.000	.008	.239	.303	.257		.013	.015
receptor-9	Correlation	-.124**	-.026	-.031	.028	-.060	.837**	.723**	-.561**	.094*	-.053	-.026	.048	.[a]	-.076*	-.091*
	Significance	.001	.268	.227	.249	.077	.000	.000	.000	.012	.104	.268	.126		.035	.014

**. Correlation is significant at the 0.01 level (1-tailed).

*. Correlation is significant at the 0.05 level (1-tailed).

Table 43 - case-4 receptors - Correlation of Variables to Mean Radiant Temperature

case-4		u	v	w	wSpeed	wDir	T	q	q.rel	SVF	BSF	ISF	PSF	GSF	HRE	FAR
receptor-1	Correlation	-.099**	-.076*	-.077*	.068	-.005	.816**	.751**	-.359**	.176**	-.019	.025	.008	.008	-.178**	-.176**
	Significance	.009	.034	.032	.052	.456	.000	.000	.000	.000	.325	.272	.420	.421	.000	.000
receptor-2	Correlation	-.077*	-.043	.166**	.045	-.037	.857**	.757**	-.637**	.169**	-.045	.085*	-.115**	-.115**	-.096*	-.104**
	Significance	.032	.150	.000	.143	.185	.000	.000	.000	.000	.141	.020	.003	.003	.011	.006
receptor-3	Correlation	.098**	-.078*	-.034	-.081*	-.040	.838**	.756**	-.520**	.165**	-.060	-.001	.053	.054	-.122**	-.133**
	Significance	.009	.030	.211	.025	.171	.000	.000	.000	.000	.076	.494	.100	.098	.002	.001
receptor-4	Correlation	-.059	.034	-.018	-.058	-.018	.924**	.821**	-.776**	.133**	-.052	.038	.026	-.032	-.103**	-.119**
	Significance	.079	.206	.335	.082	.337	.000	.000	.000	.001	.108	.181	.266	.222	.007	.002
receptor-5	Correlation	-.036	-.007	-.038	-.001	.004	.815**	.691**	-.439**	.117**	-.028	-.015	.036	.054	-.103**	-.109**
	Significance	.194	.435	.180	.490	.462	.000	.000	.000	.003	.249	.361	.195	.099	.007	.004
receptor-6	Correlation	-.060	-.026	-.021	.021	-.007	.833**	.723**	-.465**	.156**	-.013	.031	-.050	-.014	-.137**	-.136**
	Significance	.076	.270	.304	.306	.434	.000	.000	.000	.000	.381	.231	.118	.373	.000	.001
receptor-7	Correlation	-.018	.087*	.091*	-.099**	.004	.877**	.743**	-.626**	.123**	-.058	.055	.030	-.037	-.101**	-.118**
	Significance	.331	.018	.014	.009	.458	.000	.000	.000	.002	.082	.094	.233	.186	.008	.002
receptor-8	Correlation	.009	-.005	.158**	.002	.002	.807**	.689**	-.575**	.098**	.033	.019	-.027	-.020	-.089*	-.086*
	Significance	.417	.453	.000	.481	.479	.000	.000	.000	.009	.214	.327	.258	.315	.016	.019
receptor-9	Correlation	-.073*	-.013	-.008	.012	-.053	.852**	.751**	-.612**	.092*	-.052	-.015	.040	-.026	-.076*	-.091*
	Significance	.041	.374	.427	.390	.104	.000	.000	.000	.014	.107	.361	.166	.269	.034	.015

**. Correlation is significant at the 0.01 level (1-tailed).

*. Correlation is significant at the 0.05 level (1-tailed).

center of the urban block. (Fig. 69) The comparison is also extended to encompass streets on particular direction of a block. e.g. - north-south street on the west of a block

<u>All streets- (under case1background conditions) (Table 44)</u>

Fig. 70 demonstrates the change in MRT throughout the day for all street receptors. The center of the block (c) has a distinct difference to those of the streets bounding the sites (east-west /south (ew s), east-west / north (ew n), north-south / east (ns e), north-south / west (ns w)) the center being considerably cooler throughout the day. Understandably, the warmest trend is seen in the north-south streets on the west side of the block (ns w), especially in the afternoon hours. Similarly, the east-west

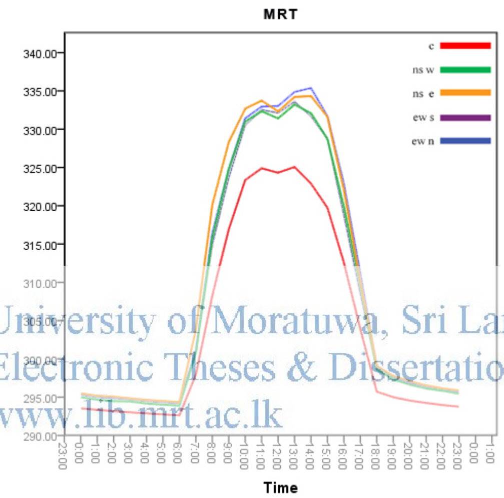


Fig. 70 - case1—all streets comparison
- MRT to Time relationship

oriented street on the south side (ew s) too is comparatively warm throughout the day.

The microclimate changes in the nighttime hours for the street cases follow a similar trend, while the center of the block is considerably cooler.

Correlation Analysis -

The variable correlation to MRT (Table 44), follow a similar trend as above where, the center of the block has the strongest correlation. The warmer receptor groups have the weaker correlation. SVF has the strongest correlation among morphology variables.

Table 44 - case1 - Street Orientation Series - Correlation of Variables to Mean Radiant Temperature

case		u	v	w	wSpeed	wDir	T	q	q.rel	SVF	BSF	ISF	PSF	GSF	HRE	FAR
centre c	Correlation	-.113**	-.064	-.076*	.057	-.016	.817**	.757**	-.519**	.160**	-.021	.025	.010	.[a]	-.162**	-.161**
	Significance	.003	.064	.034	.084	.350	.000	.000	.000	.000	.311	.277	.405		.000	.000
ns east	Correlation	-.031	-.021	.085**	.016	-.018	.850**	.730**	-.673**	.134**	-.028	.059**	-.056**	.[a]	-.098**	-.103**
	Significance	.098	.189	.000	.249	.225	0.000	.000	.000	.000	.123	.007	.010		.000	.000
ns west	Correlation	-.045*	.012	.006	-.019	-.036	.866**	.740**	-.692**	.110**	-.052*	.010	.043*	.[a]	-.085**	-.100**
	Significance	.031	.313	.400	.212	.068	0.000	.000	.000	.000	.015	.335	.036		.000	.000
ew north	Correlation	.000	-.025	-.018	.000	-.010	.860**	.777**	-.698**	.129**	-.042*	.034	.013	.[a]	-.106**	-.117**
	Significance	.493	.152	.222	.498	.336	0.000	0.000	.000	.000	.041	.079	.293		.000	.000
ew south	Correlation	-.037	-.025	.052*	.021	-.010	.824**	.719**	-.639**	.098**	-.038	.014	.011	.[a]	-.082**	-.091**
	Significance	.060	.151	.015	.191	.336	0.000	.000	.000	.000	.056	.278	.324		.000	.000

**. Correlation is significant at the 0.01 level (1-tailed).

*. Correlation is significant at the 0.05 level (1-tailed).

Table 45 - case2 - Street Orientation Series - Correlation of Variables to Mean Radiant Temperature

case		u	v	w	wSpeed	wDir	T	q	q.rel	SVF	BSF	ISF	PSF	GSF	HRE	FAR
centre c	Correlation	-.105**	-.070*	-.078*	.062	-.013	.818**	.755**	-.518**	.159**	-.017	.023	.008	.008	-.160**	-.159**
	Significance	.006	.045	.031	.070	.377	.000	.000	.000	.000	.338	.291	.426	.427	.000	.000
ns east	Correlation	-.035	-.022	.075**	.017	-.017	.848**	.727**	-.663**	.134**	-.028	.058**	-.054*	-.051*	-.097**	-.103**
	Significance	.070	.184	.001	.241	.238	0.000	.000	.000	.000	.121	.008	.012	.016	.000	.000
ns west	Correlation	-.047*	.012	-.003	-.019	-.029	.865**	.738**	-.686**	.111**	-.052*	.011	.044*	-.015	-.086**	-.102**
	Significance	.026	.312	.445	.217	.116	0.000	.000	.000	.000	.015	.326	.035	.271	.000	.000
ew north	Correlation	-.002	-.024	-.023	.001	-.005	.859**	.777**	-.694**	.128**	-.042*	.033	.015	-.015	-.106**	-.117**
	Significance	.468	.155	.169	.490	.414	0.000	0.000	.000	.000	.041	.086	.269	.267	.000	.000
ew south	Correlation	-.039	-.025	.039	.022	-.005	.823**	.718**	-.633**	.099**	-.040	.014	.012	-.022	-.082**	-.092**
	Significance	.052	.146	.050	.181	.419	0.000	.000	.000	.000	.050	.275	.313	.177	.000	.000

**. Correlation is significant at the 0.01 level (1-tailed).

*. Correlation is significant at the 0.05 level (1-tailed).

Statistical Significance -

The surface characteristic variables are not significant, except in the north-south/east street, where ISF and PSF become significant. The PSF is also significant in the north-south/west oriented street.

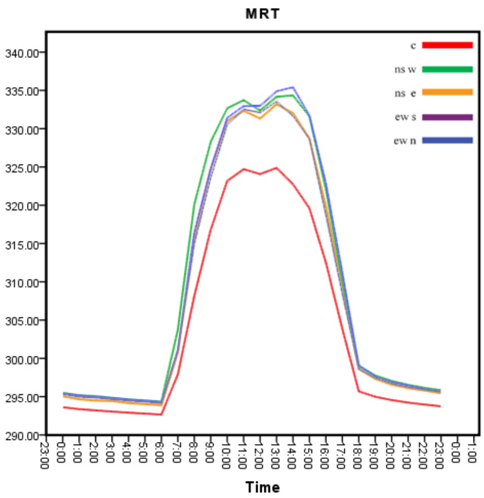


Fig. 71 - case2—all streets comparison - MRT to Time relationship

<u>All streets- (under case2 background conditions) (Table 45)</u>

case2 (Fig. 71) follows a similar pattern to that of case1 (Fig. 70). The overall behaviour of MRT throughout the day, too follow a similar trend to that of case1.

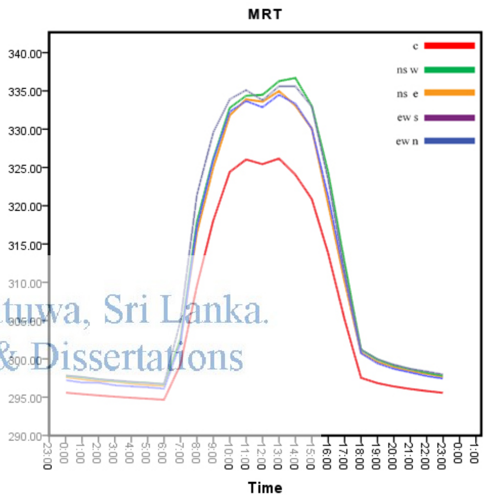


Fig. 72 - case3—all streets comparison - MRT to Time relationship

<u>All streets- (under case3 background conditions) (Table 46)</u>

The trend lines follow a similar pattern to that of case1 and case2, while, value differences are seen only in the peak hours of the day and the nighttime hours (Fig. 72).

The comparison between case2 and case3 (Fig. 73) show that the rates of change as well as the values correspond, for the hours where the microclimate is rapidly warming up and cooling. (Day - between 07.00hrs. to 10.00hrs and night - 16.00hrs. to 18.00hrs.). All the street receptor combinations show similar trends and values, within this period.

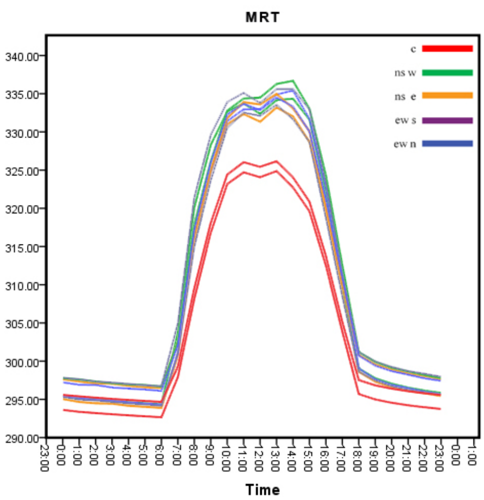


Fig. 73 - case2 to case3 streets comparison - MRT to Time relationship

Table 46 - case3 - Street Orientation Series - Correlation of Variables to Mean Radiant Temperature

case		u	v	w	wSpeed	wDir	T	q	q.rel	SVF	BSF	ISF	PSF	GSF	HRE	FAR
centre c	Correlation	-.105**	-.063	-.086*	.055	-.020	.816**	.754**	-.367**	.177**	-.020	.026	.009	.[a]	-.179**	-.177**
	Significance	.006	.065	.020	.093	.317	.000	.000	.000	.000	.317	.268	.414		.000	.000
ns east	Correlation	-.030	-.021	.095**	.016	-.015	.853**	.730**	-.609**	.146**	-.031	.062**	-.056**	.[a]	-.107**	-.113**
	Significance	.103	.191	.000	.252	.265	0.000	.000	.000	.000	.099	.005	.010		.000	.000
ns west	Correlation	-.045*	.012	.010	-.020	-.034	.868**	.741**	-.626**	.121**	-.059**	.017	.047*	.[a]	-.093**	-.112**
	Significance	.032	.306	.335	.206	.076	0.000	.000	.000	.000	.007	.243	.026		.000	.000
ew north	Correlation	.001	-.028	-.009	.003	-.008	.861**	.778**	-.628**	.143**	-.050*	.040*	.017	.[a]	-.116**	-.129**
	Significance	.479	.123	.350	.455	.376	0.000	0.000	.000	.000	.020	.046	.244		.000	.000
ew south	Correlation	-.039	-.027	.055*	.024	-.013	.826**	.721**	-.561**	.110**	-.047*	.019	.011	.[a]	-.093**	-.104**
	Significance	.052	.129	.011	.161	.301	0.000	.000	.000	.000	.024	.214	.323		.000	.000

**. Correlation is significant at the 0.01 level (1-tailed).

*. Correlation is significant at the 0.05 level (1-tailed).

Table 47 - case4 - Street Orientation Series - Correlation of Variables to Mean Radiant Temperature

case		u	v	w	wSpeed	wDir	T	q	q.rel	SVF	BSF	ISF	PSF	GSF	HRE	FAR
centre c	Correlation	-.099**	-.076*	-.077*	.068	-.005	.816**	.751**	-.359**	.176**	-.019	.025	.008	.008	-.178**	-.176**
	Significance	.009	.034	.032	.052	.456	.000	.000	.000	.000	.325	.272	.420	.421	.000	.000
ns east	Correlation	-.039	-.022	.101**	.020	-.018	.830**	.707**	-.537**	.149**	-.029	.060**	-.051*	-.048*	-.110**	-.116**
	Significance	.051	.178	.000	.198	.224	0.000	.000	.000	.000	.111	.006	.017	.024	.000	.000
ns west	Correlation	-.059**	.028	.003	-.040*	-.037	.881**	.754**	-.647**	.119**	-.062**	.014	.040*	-.026	-.092**	-.111**
	Significance	.007	.120	.457	.048	.064	0.000	0.000	.000	.000	.005	.280	.048	.139	.000	.000
ew north	Correlation	.029	-.038	.016	.018	.011	.849**	.741**	-.529**	.149**	-.061**	.053*	.002	-.032	-.121**	-.137**
	Significance	.110	.056	.259	.230	.328	0.000	.000	.000	.000	.006	.013	.475	.089	.000	.000
ew south	Correlation	-.042*	-.023	.027	.018	-.015	.824**	.710**	-.530**	.108**	-.046*	.016	.021	-.016	-.091**	-.102**
	Significance	.041	.171	.135	.227	.265	0.000	.000	.000	.000	.027	.255	.187	.258	.000	.000

**. Correlation is significant at the 0.01 level (1-tailed).

*. Correlation is significant at the 0.05 level (1-tailed).

For the center receptor too, the rapid warming and cooling hours of the day are closer in value than those of the peak and night hours. Case3 is warmer for the hours that differ.

<u>All streets- (under case4 background conditions) (Table 47)</u>

Although, the behaviour of the street receptors show a similar trend (Fig. 74), case4 differs to case3. This factor was not seen in analyses series considered up to this stage. case3 and case4 usually corresponded in both value and trend.

The comparison between cases (Fig. 75) show that for case4 streets show differing characteristics during the day.

- Centre receptor (c) - case4 is slightly cooler during the day, but show similar values during the night.
- North/south-east receptor (ns e) - case4 is cooler for the second half of the day. For the morning hours, it is slightly warmer.
- North/south-west receptor - case4 is warmer for the second half of the day, but cooler for the morning hours. The peak value for this receptor combination is the warmest for all receptors. Conversely, it is also the coolest for the morning hours.
- East/west - north receptor - shows little or no variation between cases. The maximum variation, though minimal is seen between 09.00hrs. and 11.00 hrs.
- East/west- south receptor - shows little or no variation between cases. Overall, it is minimally cooler, yet

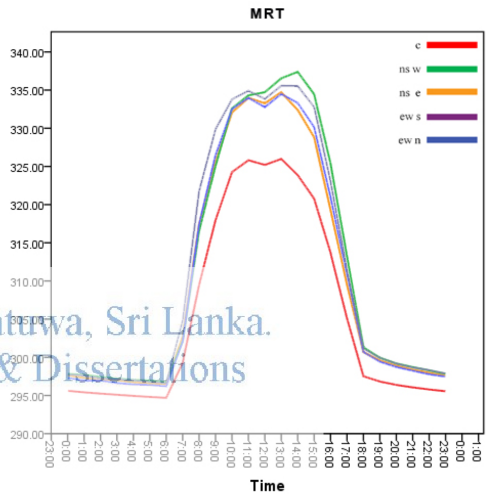


Fig. 74 - case4—all streets comparison - MRT to Time relationship

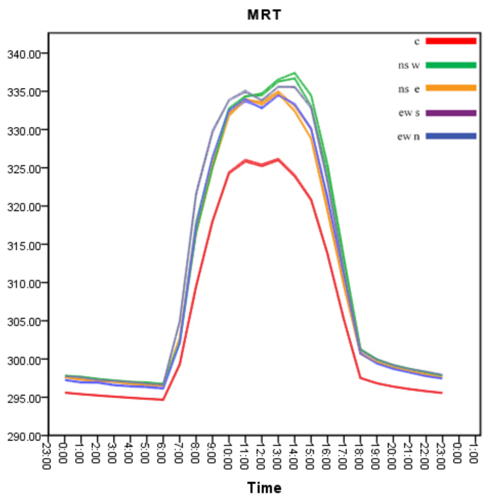


Fig. 75 - case3-case4 streets comparison - MRT to Time relationship

following a similar variation pattern to that of case3. East west streets along the south boundary of an urban block are warmer throughout the day than other street edges. It is only minimally cooler than that of the North/south-west receptor for the afternoon hours.

Correlation Analysis -

For both case3 and case4, the cooler streets have the stronger correlation to the variables SVF, HRE and FAR. The warmer receptor groups have the weaker correlation. The hierarchy of the variables, in relation to MRT does not change between cases.

Statistical Significance -

The surface characteristics are not significant for most streets.

- BSF - shows an increase in correlation for case4 and is significant for the (ns w), (ew n) for both cases. (ew s) becomes significant for case4 only.
- ISF - (ns e) is significant for both cases, while ew north becomes significant for case4 only.
- PSF - is significant for (ns e) and (ns w) only, for both cases. The correlation decreases in case4 in comparison to case1.
- GSF - is significant only for the (ns e) street receptors.

<u>Discussion</u>

The warmest value is seen in the afternoon hours of the north/south oriented west facing (ns w) street. Although, the east/west oriented south facing (ew s) streets are warmer for the more hours of the day. Overall it is clear that the streets and therefore edges of an urban block are effected by its orientation and canyon geometry, as also seen in cooler centre receptor values.

The increased 'green surface cover' in the global warming background scenario, has a cooling effect on the microclimate for all receptors, especially in the afternoon hours. This was not seen in the total series, site series or model series analyses.

4.5 Summary of findings - similarities / variations to other studies and links to LCZ classification

The analyses encompassed a series of scenarios where the primary objective was to ascertain the sensitivity of specific variables, in a changed microclimate. The research is focussed on warm humid Colombo. Mean Radiant Temperature (MRT) is taken as the indicator of thermal comfort in the urban outdoors in general and streets as public spaces in particular. Each pattern highlighted from the case studies are equated to existing knowledge and to its relationship to the LCZ classification and local warming findings generated in preceding sections (Chapter 3) of this thesis.

Specific patterns highlighted across the case study series;

1. In general, night-time shows better correlation with MRT
2. The rate at which MRT changes for the hours that the microclimate rapidly warms and cools during the day show little or no variation between cases.

3. Among specific cases, case4 - green global warming scenario shows stronger correlation of variables with that of MRT.
4. The Sky View Factor (SVF) shows the strongest correlation to MRT.
5. The characteristics of the surface cover in general and 'green' surface cover in particular, has little or no effect in reducing the MRT intensity in the urban outdoors.
6. Overall context to Individual site correlation characteristics do not show a distinct pattern.
7. In general, taller buildings at the edges of urban blocks have a positive impact.
8. Within urban blocks, variations are clear in terms of orientation and canyon geometry.

1. In general, night-time shows better correlation with MRT

The greatest consequence of the change in the microclimate conditions, warmer by 2.4 ^{0}C, is seen in the 'night-time' hours of the day.

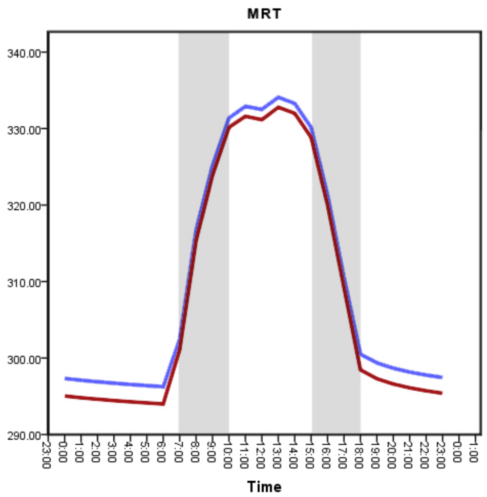


Fig. 76 - Total case series - overlapping warming and cooling zones - MRT to Time relationship

The data was generated for a single day in April was analysed for its MRT change in relation to a 24-hour period. Interpolated regression curves (Fig. 76) show distinct time zones within the day. 'Night-time' defined as the period where the suns radiation is not an influence, the warming and cooling hours of the day (shaded grey in Fig. 76) and the peak hours.

In all case study series investigated (overall, site, model and receptor series), the pattern showed a similar trend between cases, when the background conditions changed from the 'existing' to 'global warming' scenario. The MRT intensity seen in the 'global warming' case always exceeded that of the 'existing' case for the night-time hours.

The coefficient of correlation between morphology variables grew stronger at night-time, while the correlation to climatic variables weakened. Therefore, it shows that in terms of correlation, the adoption of morphology variables to ameliorate negative effects is applicable for both, daytime and night-time.

This is especially seen in the Model/ Case series (Fig 4.22), where the morphology models of case4 was compared to that of case1. Here, though the MRT intensity of many of the morphology models was lower than the existing condition during the day, the values always exceeded the existing for the 'night time hours. This is found to be true even for an urban context with an extensive 'green' surface cover.

The main implication of this is that, though modified morphology options can help adopt to, or even roll back the negative effects of a warmer microclimate during the daytime hours, the influence is deemed inadequate for the night-time hours, where the microclimate remains warmer than the existing case.

Similarities / variations to other studies -

The distinct patterns seen in the night-time highlighted in the analysis are found true for other studies in the tropics. Thus, confirms established thinking on the area. Presented below are selected studies that give insight on these factors of warmer night-time hours and parameters that drive the phenomenon.

Night-time local warming is typical of the UHI phenomenon. It has been shown, that UHI is strongest under clear skies and calm winds. Emmanuel (2006) states; "Although the nocturnal UHI is well studied, the daytime urban climate has received less attention. In general, the urban–rural differences are smaller by day than by night, and the city can be either warmer or cooler than the rural surroundings" (Emmanuel & Johansson, 2006).

Giridharan (2005) in Hong Kong, found that; "During the extended summer, critical variables that could mitigate the nocturnal UHI are NRDF (total non-residential area to total floor area ratio of the development), location quotient, sky view factor and vegetation above 1m in height". (Giridharan, 2005).

Location quotient (LQ) is basically a way of quantifying how concentrated a particular industry, cluster, occupation, or demographic group is in a region as compared to the nation. It can reveal what makes a particular region "unique" in comparison to the national average. (Economic Modelling Specialists Inc.,)

The LQ, is defined by Giridharan (2005) as the territorial population that has an impact on the UHI of a particular place. In his study, he represents the territorial impact through the LQ. If the LQ value is high, the territorial development impact on a proposed development is high. Generally the lower the LQ, larger the thermal stress on the environment.

LQ = (PP/PR) / (PL/PT)

- PP- Population in the project
- PR-Total population within a 300m radius of the project.
- PL-Total population in the local area.
- PT-Total population of the territory

(Giridharan, 2005)

In consideration of LQ in the context of Colombo, Sri Lanka, it is assumed that the impact on UHI will be very high in comparison to other cities in the country. Colombo is the primate city of Sri Lanka and therefore has the highest population and population density.
(Fig. 77)

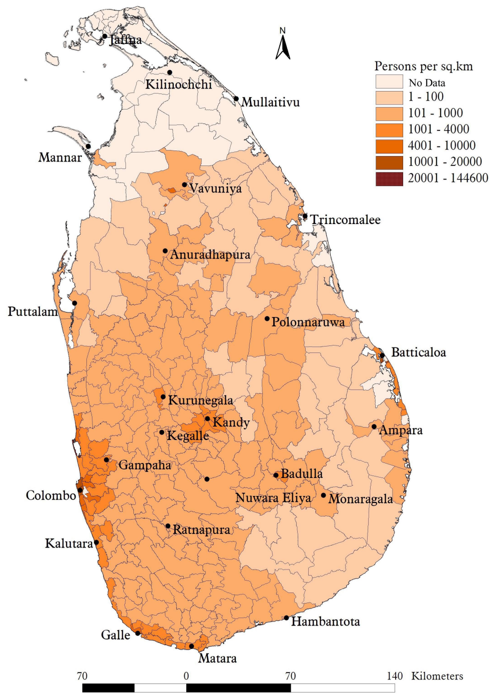


Fig.. 77 - Sri Lanka population density
(Source - columbia.edu)

Tan (2013), observed MRT fluctuations in the urban environment in relation to urban constituents such as greenery and large water bodies. While proven to effectively reduce the ambient temperature of its surroundings throughout the day, green cover and water do not affect MRT significantly after nightfall. They conclude that the 'MRT does not differ significantly in the absence of sunlight and therefore any attempt to lower MRT should logically be done only in daytime'. (Tan et al, 2013)

Links to LCZ classification and local warming;

The effect on the night-time conditions were clearly seen in the local warming highlighted in the LCZ classification in section 3.2.3.The numerical simulation using the SHIM analysed the rate of which the urban fabric could release the stored radiation in the night-time hours. A change in LCZ from a low-density zone to a higher density zone always pushed the UHI intensity up.

2. The rate at which MRT changes for the hours that the microclimate rapidly warms and cools during the day show little or no variation between cases.

For most analysis series, the MRT rapidly warms between 06.00 hrs. to 10.00 hrs. and rapidly cools between 15.00 hrs. to 18.00 hrs. (Fig. 76) The analyses show that rate of change is relatively similar for the period between 07.00 hrs. and 10.00 hrs. In all four background climate cases, which includes the 'global warming' background case, show a similar trend. This also holds true for overall, site, morphology models, receptor series simulated.

The MRT intensity differences are distinct for night-time and at the peak hours of the day.

The implication is that, even in a future scenario with a marked change in background temperature, the MRT of the particular time interval, (07.00 hrs. to 10.00 hrs. and 15.00 hrs. to 18.00 hrs.) remains relatively unaffected.

Therefore, in comparison to the existing situation, for up to 6 hours of the day, the microclimate does not differ adversely, making the task of mitigating and adapting to global warming that much easier. Yet, the question arises; will this have implications outside these hours? Can the warming and cooling be controlled / lessened to have a positive effect in the night-time and peak hours of the day?

3. Among specific cases, case4 - green global warming scenario shows stronger correlation

Overall the correlation between MRT and the morphology variables strengthen in a microclimate affected by global warming, thereby enhancing the capacity for prediction. Correlation to MRT is strongest for the 'green global warming' climatic background scenario (case4) for all analysis series considered. Oke, (1987) found that urban geometry is “a fundamental control on the urban heat island”. This is seen true for a future, warmed climate too.

4. The Sky View Factor (SVF) shows the strongest correlation to MRT

Only **v** [Wind speed v-component (south to north)] of the climatic variables and Sky View Factor (SVF) of the morphology variables remain relevant for all simulation case scenarios considered. Therefore, in a morphology-based approach to reducing MRT in the urban outdoors, SVF needs to take precedence.

Similarities / variations to other studies -

Various studies show that sky view factor as an important tool in urban geometry manipulation (Oke, 1987). Oke, demonstrated that there is a strong relationship between many high-density city populations and the sky view factor. Theoretically, sky view factor will be low where density is high. Oke identifies the following formula "expressing the urban heat island intensity as a function of the SVF" (Givoni, 1998): dT =15.27-13.88*SVF

"The above formula expresses the hypothesis that the urban heat island is caused by reduced radiant heat loss to the sky from the ground level of density built urban centres, where the heat island phenomenon is observed and measured, due to the restricted view of the sky" (Givoni, 1998; Wu, 2009)

The findings of the sensitivity analysis confirm the impact of SVF as a primary variable for UHI mitigation and outdoor thermal comfort.

Links to LCZ classification and local warming;

The LCZ classification and local warming analysis was focused on the night-time cooling capacity of the urban surfaces. In this instance the LCZs with higher SVF was the slowest to cool, thus, showing an increased intensity in the temperature difference.

The implications of this is in utilising higher density built edges and urban blocks (with lower SVF) for shading of the public spaces during the day and its impact on the reduced cooling ability of built morphology in the night-time hours.

5. The characteristics of the pervious surface cover in general and 'green' surface cover in particular, has little or no effect in influencing the overall correlation of variables with MRT.

Simulations adopting a change in pervious surface cover, specifically where the open soil covered non-built areas of a urban block was replaced by a 'green' surface with a uniform 50mm thick dense grass cover, had little or no effect on the correlation of variables with that of MRT. This was seen for both the existing case scenario as well as the 'global warming' scenario.

PSF was seen as 'not significant' for most analysis series. Yet, ISF and GSF were shown to be statistically significant.

Thus, other driving factors are more predominant in relation to the MRT change, than the nature of the pervious surfaces.

In terms of the correlation of morphology variables, the 'green' cases saw an increase in the strength of the coefficients between the 'open soil' case to 'green' case, in the range of 0.001. This was found to be true for both existing and global warming scenarios. The correlation of the climatic variables experienced an opposite effect, where the correlations weakened between 'open soil' and 'green' cases. The correlation change in the climatic variables were more pronounced.

The implication of this is that, of the morphology variables, the three-dimensional, geometric variables take precedence over the surface characteristic variables. (see Table 15)

Similarities / variations to other studies -

(Oke et al, 1981) shows that although many types of surfaces abound in urban areas, only two matter in terms of the heat island: natural and manmade. Within the manmade surfaces, they found little correlation between types of surfaces and heat island effect.

(Middel et al., 2012) exploring Urban form, landscape design, and microclimate in Phoenix, Arizona, states; "This implies that pervious surfaces with or without grass can balance temperatures locally".

Noting that the urban geometry factors have not received as much consideration in explaining the spatial temporal distribution of urban heat islands as have surface materials, (Todhunter, 1990) takes the position that at a microscale, explicit considerations of urban geometry are more important. At the mesoscale, however, he argues that both the geometry and surface thermal characteristics play an equal role. (Emmanuel, 1993)

Links to LCZ classification;
The LCZ classification explored the effect of the surface cover, especially for the LCZs that had extensive open area between built forms, as a sub-categorisation of the LCZ. The transformation of the UHI intensity was generated mainly by the change in the input values for emissivity and thermal admittance of the urban canyon materials. A sub categorisation with LCZs of the natural series (A-dense trees, B-Scattered Trees, C-Bush, Scrub, D-Low Plants, E-Bare Rock or Paved, F-Bare Soil or Sand, G-Water) as the secondary category generally reduced the intensity of UHI. An exception to the pattern is seen in LCZ-E (Bare Rock or Paved) where it pushed the intensity up. (see Table 10). As mentioned in the earlier section, the local warming utilises temperature as the measure.

Here the difference is between LCZ-F (Bare soil or sand) and LCZ-D (low plants) in terms of nocturnal cooling capacity and therefore UHI intensity is distinct.

<u>6. Overall context to Individual site correlation characteristics do not show a distinct pattern.</u>

Variables of individual sites vary in their correlation to those of the overall context, therefore deemed site / zone specific. This is true for both the total day and night-time periods.

The characteristics seen in s1 have distinct differences to those of the other sites. This is seen in the relationship between MRT and morphology variables as well. Yet, behaviour of variables for site2 shows similarities to those of site3 and site4. Thus, it can be seen that the proximity of the site /zone to distinct features in the context (like the ocean in this case), affect the overall behaviour.

Similarities to other studies -

The study done in Colombo, Sri Lanka by (Emmanuel & Johansson, 2006b) found that, 'There was also evidence of a sea breeze effect; sites open to the sea were significantly cooler than other urban sites. In contrast to the daytime variations, only small intra-urban temperature differences were found at night. (Emmanuel & Johansson, 2006)

The current research, based on simulation as opposed to the on-site measurement approach adopted by Emmanuel & Johansson, reports the sea front site as warmer. It is important to note the key variables reported was temperature for the measurement based study and MRT for the current simulation study.

Emmanuel (2005) extensively discusses urban design strategies based on the relationship to natural features and landscape control.

Links to LCZ classification;

The LCZ classification encompassed morphology aspects with local level warming on clear, calm days. Therefore, no variation in UHI intensity is reported within similar LCZs in different locations in the city. This is due to the fact that, surface temperatures measured on site, in order drive the SHIM simulation was generalised for particular materials.

The implications of this is that strategies to control morphology and thereby MRT reduction, need to be site / zone specific rather than for the overall city context. The questions that arise are; would area specific urban design guidelines be needed? If so what will generate the said urban design guidelines?

7. In general, taller buildings at the edges of urban blocks have a positive impact

It was shown that urban morphology changes could help mitigate or even roll back the negative effects caused to the microclimate by global warming. The high-density options, especially when they are at the edge of the street have a better ability to cool the outdoors. The key is in the ability of the building morphology to shade the outdoors. The higher density options allow better shading possibility.

Morphology changes do not help reduce MRT for the night-time hours as much as for the day. The cooler, high density, LCZ2 (m5) model (Fig 4.22) comes closest to the existing MRT trend.

Morphology variables show a weak correlation to MRT for all models. The strongest correlation among variables considered is for SVF.

Similarities to other studies -

Studies on street canyon geometry and its relationship to thermal comfort in the street are extensively studied, in terms of; shading, using vegetation and buildings, materiality and albedo, and ventilation and pollution dispersal.

On the temporal scale, Tomita et al. (2006) showed that the effect of urban geometry (i.e. SVF) and thermal properties (such as thermal conductivity) affect the UHI at different times of the day; the effect of thermal properties is apparent in the early evening while urban geometry exerts its influence both during the daylight and evening hours. The link between urban geometry and daytime air temperature in warm climates is well documented. The effect of aspect ratio on the maximum temperature was explored by Ahmed, (2003) and Johansson, (2006) in varying contexts of hot humid Dhaka, Bangladesh and hot dry Fez, Morocco respectively. In both these studies it was shown that an increase in the aspect ratio of the urban canyon resulted in lowering of the air temperature. A similar study in Colombo, Sri Lanka, Emmanuel and Perera (2002) concluded that a deeper canyon is cooler by 2 to 6^{o}C and create an increase of over 3 hours of comfortable time in a typical day. In hot, humid Colombo, Sri Lanka, Emmanuel & Johansson (2006) found intra-urban differences in maximum daily temperatures of up to 7 K between sites of different urban geometries. (Emmanuel & Fernando, 2007a)

Further, (Emmanuel & Fernando, 2007b) found in Colombo and Phoenix that, urban density (taller buildings) has a positive mitigating effect, although it was found that it had a greater effect on MRT than air temperatures. Since MRT is critical to outdoor thermal comfort, it is likely that high density development will lead to lower thermal discomfort in the heavily built sections of these cities. This is especially true in the daytime hours where many human activities take place in urban street canyons. (Emmanuel & Fernando, 2007b)

Thus, the results of the sensitivity analysis of parameters confirm established knowledge for the tropics.

Links to LCZ classification;

The LCZ classification explored urban blocks of specific geometry and morphology for categorisation. The numerical simulation using SHIM adopted a canyon shape and material based on this classification. The analysis showed that it was the higher density options that generated the least possibility to release the stored solar radiation. Thus, making these LCZs the most critical in terms of UHI intensity they demonstrate.

The critical aspect here is that the LCZ classification used air temperature, while the simulations adopted MRT as the key variable. Therefore, though the high-density options generate a rise in nocturnal UHI, it is the best-case scenario to reduce MRT in the urban outdoors.

<u>8. Within urban block variations are clear in terms of orientation and canyon geometry</u>

The orientation of the public space and the canyon geometry is known to be crucial for comfort in the urban outdoors. It is clear that spaces with the least potential to negate the solar radiation is the worst affected. The warmest value is seen in the afternoon hours of the north/south oriented, west facing street (ns w). The east/west oriented south facing streets (ew s) are warmer for the more hours of the day, mainly due to the exposure to the sun in the morning hours.

Morphology variables show a weak correlation to MRT for all receptors.

Thus, it is evident that in the microscale, the varying morphology and orientation of the street needs to be considered in the formulation of strategies for amelioration.

Similarities to other studies -
As with the preceding section, much has been written on this aspect.

The 'shadow umbrella' concept developed by Emmanuel is exemplar effort in this regard. An outline of the concept is presented in Chapter 2.

Links to LCZ classification;
A survey and categorisation of street canyons by (Perera & Weerasekara, 2014) based on LCZ classification in Chapter 3 and (Perera et.al., 2012) identified the predominant canyon combinations and their orientation as follows (Fig. 78);

- LCZ3 - LCZ3 (Compact Low-rise- Compact Low-rise) - (33.19%)
- LCZ3 - LCZ8 (Compact Low-rise- Large Low-rise) - (11.01%)
- LCZ2 - LCZ2 (Compact Mid-rise- Compact Mid-rise) - (6.6%)
- LCZ2 - LCZ3 (Compact Mid-rise- Compact Low-rise) - (6.3%)

The potential for the simplification of the urban context using the LCZ classification is clear, making the process of generating strategies for amelioration more generic and applicable.

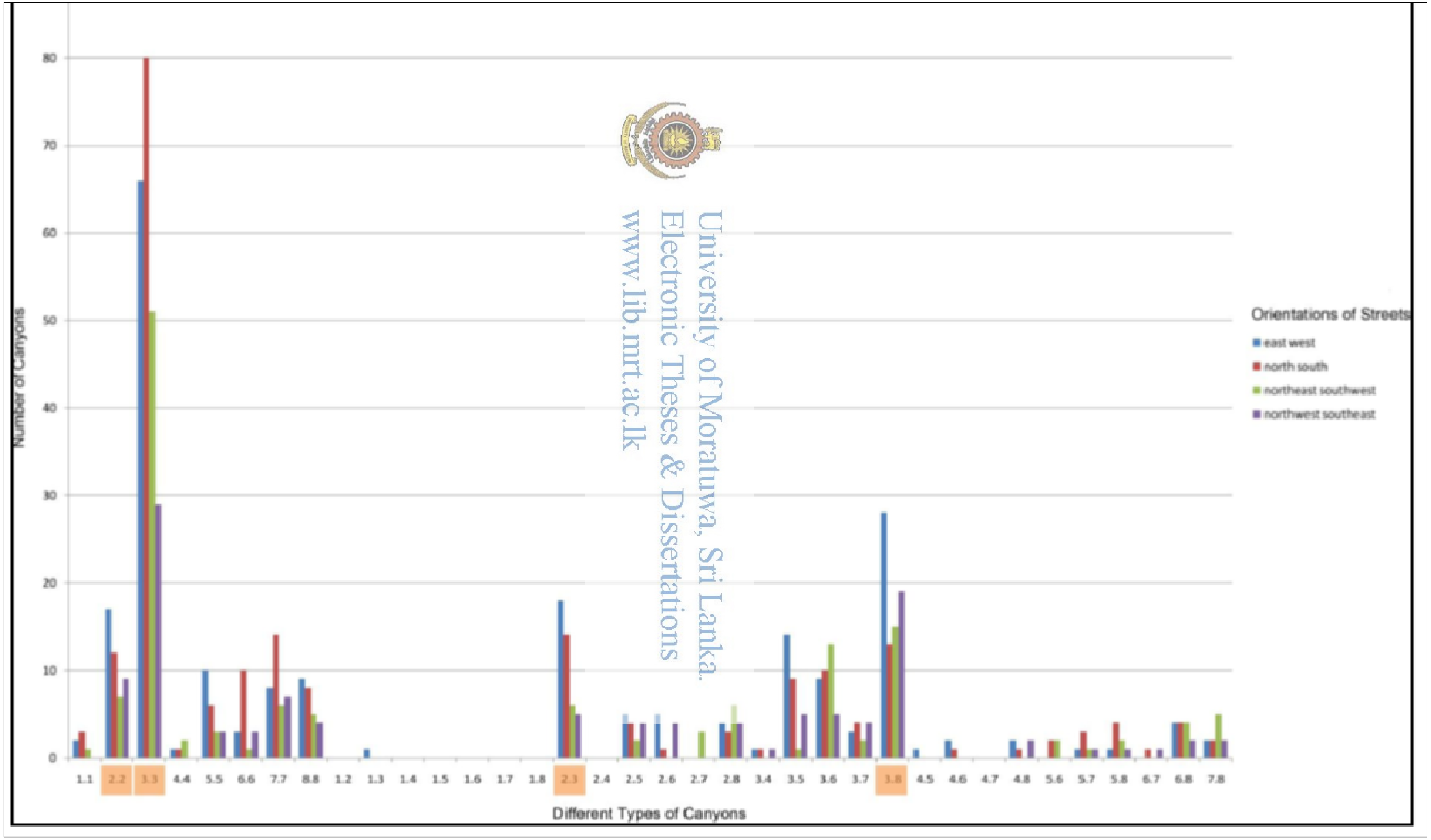


Fig. 78 - LCZ combinations and frequency of occurrence. (Source - Perera & Weerasekara, 2014)

Summary

The Chapter - Results and Discussions - presented the outcome of a research design focused on the sensitivity analysis of variables, encompassed in the LCZ classification system. The focus was on both the existing climatic context and that of the globally warmed background climate.

The discussion concludes with summary of findings, its similarities or variances to existing knowledge and its links to the LCZ mapping presented in Chapter 3.

The Chapter establishes the base from which implications for Planning and Policy is generated.

5.0 Implications for urban planning and policy

The chapter is focussed on addressing the third research question generated in the two initial chapters of the thesis. The approach encompasses the primary objective of - “bridging the gap in urban design-climate links, being translated into guidelines for real-world applicability for the warm humid tropical climate of Colombo, Sri Lanka, in a background climate affected by Global Warming”

The research question is stated as;

What are the planning and policy implications that can be generated to adapt to or roll-back the negative effects of a warmed urban microclimate?

Planning and Policy implications are based upon two primary domains established in the research;

- The research based its approach on the simplification of the context by applying the LCZ classification system for greater generality and applicability across similar contexts and climates.

- The research highlights the sensitivity of morphology variables in a background climate warmed by global warming. Therefore, any approach to ameliorate or rollback the negative effects should encompass the manipulation / control based on these variables.

The research utilised Colombo, Sri Lanka as the experimental context to explore the research questions. The application and generalisation of planning and policy directions are also based on the City.

5.1 Planning implications

Analyses and discussion for planning implications of the findings in the previous chapter draw upon the Urban Development Authority, City of Colombo Development Plans, briefly outlined in Chapter 3.1.

The urban development authority (UDA, 1999 and 2008) strategy for land use, approach the planning and regulation of the city urban fabric under four major areas;

1. Zoning Plan and Planning regulations
2. Density regulations
3. Building regulations
4. Development guide plans (DGP's)

The suggested guidelines / exemplars follow a similar strategy in their definition and are based primarily on the Local Climate Zone Classification and the range of values of the parameters / variables covered by the LCZ.

5.1.1 Zoning Plan and Planning regulations

UDA development plans for Colombo in 1999 and 2008 define the context into broad zones, based primarily on land use. While the 1999 plan defined density in terms of building height [defined as Height of roughness elements (HRE) in the current research] and restricted functions within zones, the 2008 development plan adopts a Floor Area Ratio (FAR) based approach. The allowable function / activity within a zone restriction seen in the 1999 plan was relaxed to certain extent, encouraging a much more mixed land-use.

The research findings establish Sky View Factor (SVF) as the most significant morphology variable for mitigating and adapting to local level warming in the warm humid climate of Colombo, Sri Lanka. The effectiveness of SVF is further strengthened in a globally warmed background climate as demonstrated in the research, as evidenced by the strong correlation between MRT (established as the primary variable for thermal comfort and UHI study) and SVF. Therefore, any approach to creating climate sensitive public spaces, should be based on SVF thresholds.

Local Climate Zones and context specific guidelines for UHI mitigation and climate sensitive public spaces

Given the consideration of urban morphology, activity, thermal properties and building geometry, LCZ mapping could provide a superior basis for climate-sensitive and context-specific urban planning. While the current planning approach is issue specific (such as zoning – in terms of activity, density – in terms of floor area ratio, or morphology parameters – such as building height, setback, etc.), an LCZ-based approach could integrate several key planning parameters and provide the rationale for a context-specific planning approach.

a. LCZ mapping and identification of critical areas

The research showed that LCZ mapping of an urban context, albeit the whole city has far ranging advantages. The most important factor is, in a LCZ mapped context is the form and therefore variances in the built fabric are easily identified. The climatic nature of the classification offers a distinct opportunity for intervention at both the geometric and the climatic realms.

i. *Identification of critically stressed areas*

The occurrence of zones classified as LCZ1 for example has a negative effect on UHI. LCZ1 could be expected to be hotter, given the concentration of anthropogenic heat in limited areas of the city.

The development projections for the City are not encouraging with greater number of areas earmarked for intensive development. (see Section 3.1.2 - Fig. 3.3). Yet, the option of a high-rise development (HRE > 25m in the LCZ system) is difficult to be avoided from a city context.

LCZ1 – compact high-rise can be avoided by utilising Open-set High-rise (LCZ4) as a better, alternate option, zoned as spaced out planned areas of the city. Thus, avoiding high-rise 'walls' in key areas of the city. (see Table 10). Although the LCZ4 too leads to comparatively high UHI intensities, the negative effects can be controlled by converting them into LCZ4 sub classified with surface cover LCZs, such as LCZB or LCZD. (see Section 3.1.4 and Table 10)

Sub classification of critical LCZs as the secondary zone can have a lesser impact, given that the characteristics remain closer to the primary - lower density, less UHI intensive - LCZ. The heterogeneity created by such an urban block, thus differences in SVF, has the advantage of shade possibilities in the day time and better radiation loss in the night. (see Section 4.5; 4)

ii. *Controlling / restricting LCZ change that drives the UHI intensity by large margins*

The LCZ classification of the city of Colombo showed the majority of the city as LCZ2, LCZ3 and LCZ8. It also showed a change of zone from a lower to a higher density pushes the UHI intensity up. (see Table 10). The greatest change in UHI intensity of 4.09°C is seen when LCZ7- lightweight low-rise is transformed in to LCZ1- compact high-rise areas. (Perera et al., 2013) This was demonstrated in a study by Perera et al., 2013 investigating the UHI effect of the UDA 2020 plan for Colombo. The differences hold true as inter LCZ differences discussed above.

This phenomenon of underserved areas being transformed into high-rise housing developments are seen in most of the developing world, and Colombo is no exception. The main objective seems to be to free underutilised land for development, the strategy could have a negative impact on the climate. A similar impact applies to LCZ8 (large low-rise, typically warehouses in the city) that change into LCZ1 or LCZ4, creating a UHI intensity increase of 3.3 °C and 3.25 °C respectively.

A socially accepted strategy in the attempt to re-house the under-served settlements is to adopt high-density walk-up housing. For example, transforming LCZ7 into LCZ3 will increase the UHI intensity by 2.88 °C; however, this seems to be the least harmful change. Transforming of more compact areas of the city, namely LCZs 2, 3 and also LCZ5 to either LCZ1 or LCZ2, seems to experience a lesser impact in terms of UHI intensity.

To avoid such negative consequences, patterns that have limited impacts can be adopted. The change of LCZ7 into open low-rise (LCZ6: 1.56 °C change) or large low-rise (LCZ8: 0.79 °C change). Options for such developments include educational or similar institutional functions, high-end housing areas, mixed developments with large green spaces and reduced vehicular traffic.

iii. *Preservation of LCZs in the built fabric*

A LCZ-based zoning approach highlights areas that need preservation. Examples could include zones such as LCZ2, LCZ3 and LCZ8, further development of which would cause the increase of their heat island magnitude. For example many older parts of the city now being re-purposed in terms of use, with little or no impact on the overall morphology and therefore the LCZ; this seems to be the best strategy in terms of UHI mitigation, since almost all transformations to higher densities have negative impacts.

It would also highlight areas that could be further developed and/or re-categorized without a severe climatic impact. The LCZs could be changed to create a reduction in the UHI intensity. For example, when LCZ6 areas are transformed in to LCZ8 (a reduction of 0.77 °C can be achieved). This is currently seen in Colombo, where traditional residential areas are being transformed into mainly educational institutions, while maintaining the open spaces (high PSF, GSF) and low building heights (low HRE).

iv. *Local geographical location (its proximity to large natural features like the ocean, lakes, parks etc.), relationship to the rest of the city, development potential and current LCZ classification in their definition.*

The LCZ classification showed that the land cover series LCZs cool faster than those of the built series. It also showed that mixing of the fabric (sub classified LCZs of the surface cover series) show lower UHI intensity. (Table 10)

The sensitivity analysis demonstrated that Sky View Factor and Ventilation [Wind speed v-component (south to north)] are major drivers of MRT magnitude in the urban outdoors. [see Section 4.1 and 4.5 (4)]

The research highlights urban blocks adjacent to natural open spaces react differently to those that are relatively land-locked. Although these sites are generally negatively affected during the day, they cool at a more rapid pace at night . Thus, fulfils a main objective of UHI amelioration. [see Section 4.2 and 4.5 (6)]

The research also shows that in terms of the surface cover characteristics, the critical factor is that the ground needs to be permeable. The nature of the permeable cover, whether grass covered or open soil, has little or no effect on the overall MRT reduction. (see Section 4.5; 5)

The planning implications of these is that any approach needs focus on creating / maintaining key open spaces in the city; use them as heat sinks (low SVF areas for night time heat loss) and sources of ventilation enhancement (as signified with the correlation strength of the wind speed component)

The canyon geometry and orientation of urban blocks - covered by SVF in this thesis - is deemed important facilitate these factors in the urban fabric. Thus, on a more local scale, the between buildings play a large role on how urban outdoor spaces are impacted. (Section 4.5; 8).

Any planning intervention need to consider these zones as an integral part of the whole.

b. LCZ based Planning Parameters for UHI mitigation and climate sensitive public spaces

The LCZ classification incorporates geometric, surface characteristics together with thermal, radiative and metabolic value ranges in their selection. (see Appendix B and C) Implementation of city scale LCZ-based interventions result in achieving characteristic morphology patterns, and the incorporation of climate characteristics within the selection. The inclusion of zone specific anthropogenic impacts give insight into the advantages / repercussions in an existing as well as for a projected future scenario.

i. LCZs as Zoning precincts - defining a LCZ specific morphology and future maximum development.

Parameters within a LCZ can be controlled to achieve a desired effect. Critical areas of the city can adopt more specific and stricter controls, while other areas can be defined as ranges. These parameters can take the form of LCZ specific Density and Building Regulations (discussed in the next section)

The LCZ mapping and local warming impact (Chapter 3.1.4 and Table 10) discussion was highlighted in the UHI effect of different LCZs. The LCZ map of Colombo also showed a recognisable form to the city in the way it has developed. With the projected development for the city it is important to consider zones not only in terms of land use, but in a climatically sensitive manner.

Section 5.1.1 (a); explored in detail, the approach to LCZ mapping and identification of critical areas, with Colombo as an exemplar for its application. It identified a range of LCZ based 'Zoning Precincts', that demand a set of controls for their success. These, controls depend on the character and it relationship to both the natural and built fabric of the city.

Previous UDA development plans offer a zone wise definition and / or restriction to drive / maintain the needed morphology character, here too, a similar approach can be utilised.

c. Exemplars for utilisation

This section presents a typology of probable 'Precincts' based on Colombo as the experimental context. The precincts exemplify the needs in an approach to climate sensitive urban planning in a future, globally warmed background climate. They draw upon the findings of this research to do so. Probable zones are depicted in Fig. 79

Major precincts can be identified as follows;

1. Sea front precinct
2. Major North/south artery precincts.
3. Major East / west artery precincts
4. Open space precincts - Beira Lake, Viharamahadevi Park, cemetery/golf course precinct

As outlined above, each of these precincts focus on or is defined geographically by a natural open space or built edge of significance. Each of these precincts is detailed out for Colombo, as a generalised approach that can be replicated in cities of similar climatic and geographical setting.

1. Sea Front precinct

   Colombo's western edge dominated by LCZ2 and LCZ3, bounded by the sea for its entire length, poses a unique set of opportunities as well as problems. The precinct is bound by the marine drive on the West and the Galle Road on the East) (both major vehicular arteries). (Fig. 79, Fig. 80 and Fig. 81)

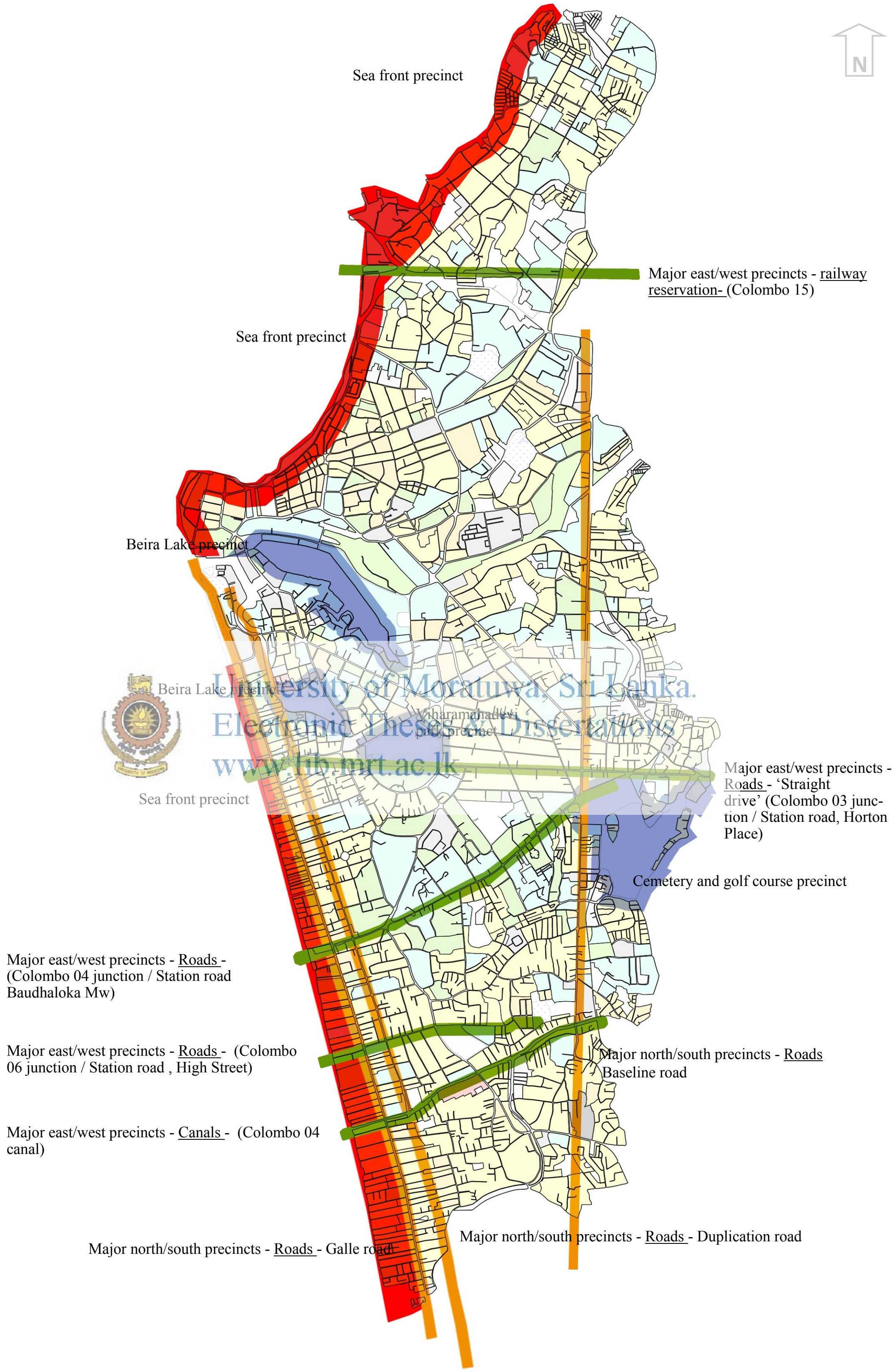


Fig. 79 - Conceptual - Map of Colombo showing exemplar / probable zoning of precincts

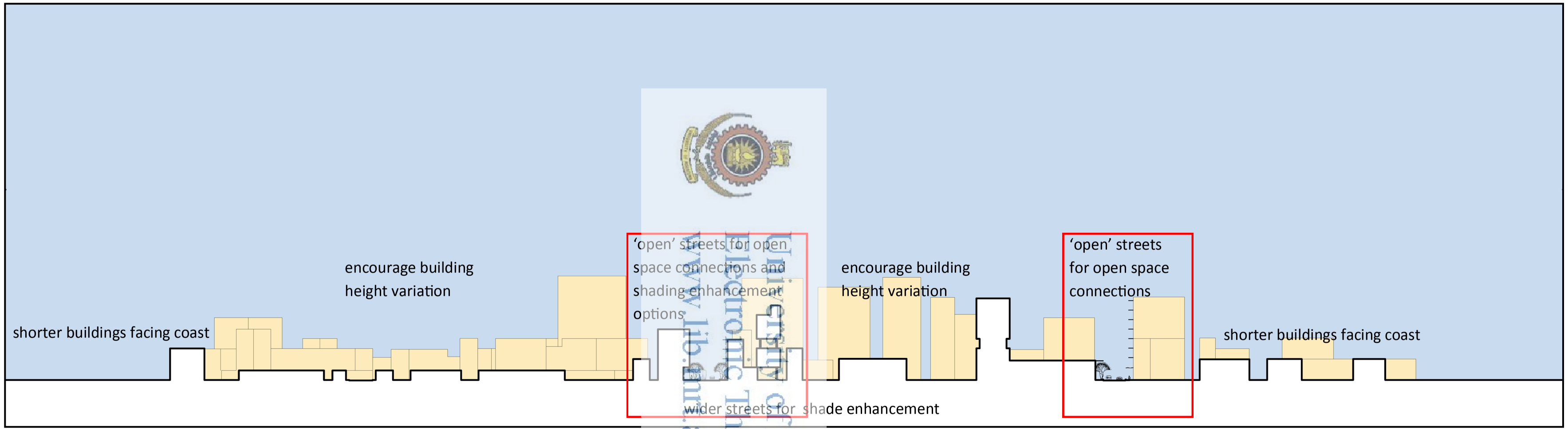


Fig. 80 - Conceptual section along Marine drive (Coastal strip), Colombo

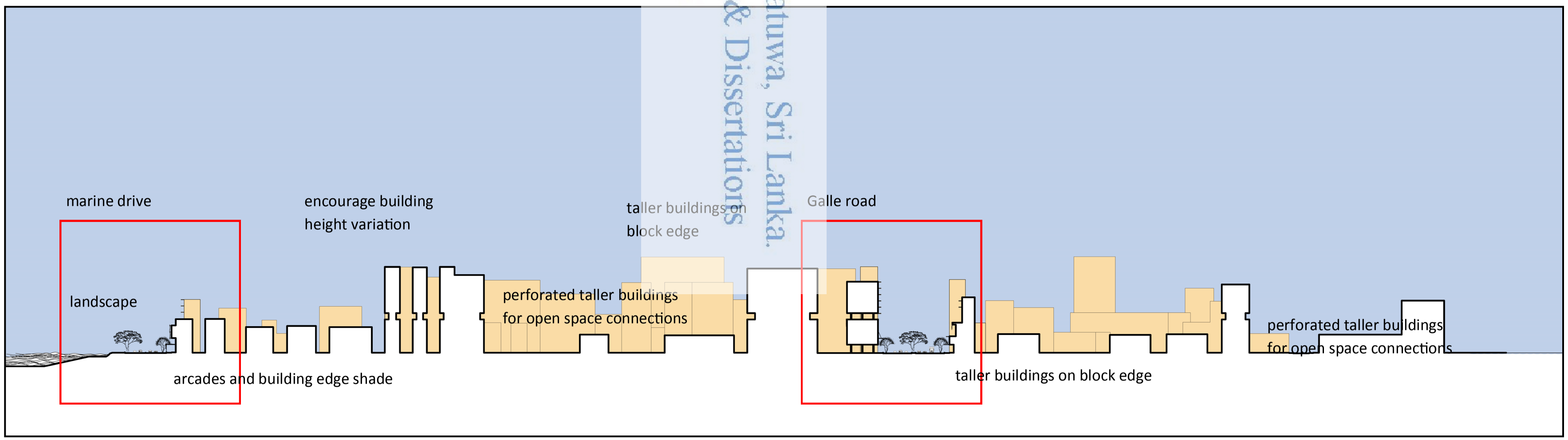


Fig. 81 - Conceptual East/West Section, Colombo

It is also seen as the fastest developing part of the city, with an alarmingly increasing number of LCZ4 being infused within the built fabric. This is due to the Marine drive, where previously, narrow, east/west oriented, dead-end streets that culminated with the railway line as the edge, has now opened up with the possibility better access and thus, through traffic. The zoning regulations restricting the use of the marine drive and height restrictions defined in the UDA plan of 1999 have also been relaxed with that of the 2008 revision to the plan. Restrictions according to plot subdivision extent, plot coverage, for example are particular to this zone in comparison to the others.

i. *Restrictions for the possibility of 'tall building walls'. Especially along the western edge of the precinct*

Although the research emphasises this the best option for shading, this edge is the most exposed (see section 4.5; 8). A totally built wall also reduce the possibility for the rest of the block and city being 'opened' up to the natural edge. The blocks in the precinct could be restricted to 'open-set' typologies - LCZ4, LCZ5, LCZ6 and LCZ8. Sub-classification is deemed advantageous.

ii. *Composite density urban blocks within the precinct to ensure building height variation and therefore, shading enhancement and SVF differentiation.*

SVF differentiation can encourage a balance between shading (low SVF) in the day and radiation loss in the night (high SVF). (see section 4.5; 1, 2, 4). Density and building regulation based on the LCZ to encourage the heterogeneous mix envisioned. Sub-classification within the precinct can be encouraged with either the LCZs of the built types or the land cover types. Recent zoning regulations stipulate a BSF of not more than 50% for new developments beyond a certain threshold.

iii. *SVF based setbacks and strategies for street level shading*

Built edges along the precinct is deemed critical for the blocks as well as the urban fabric beyond the zone

iv. *Maximizing the permeable surface cover along either side of the marine drive*

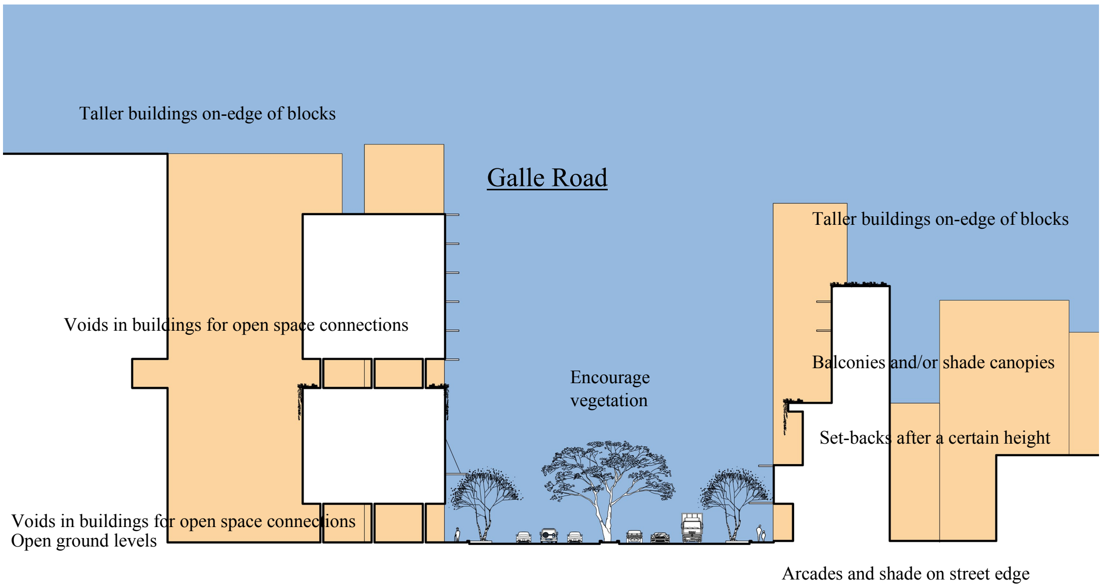


Fig. 82 - Conceptual North/South Artery Section, Colombo (Galle Road)

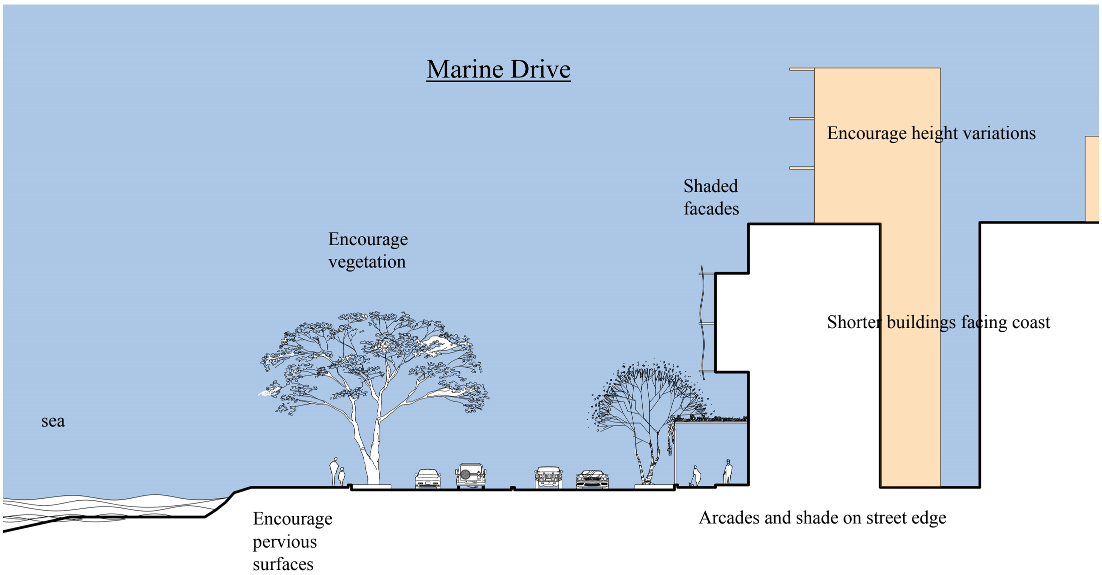


Fig. 83 - Conceptual North/South Artery Section, Colombo (Marine Drive)

The exposed, impervious surface of the marine drive can have a negative impact on the adjacent blocks as well as the rest of the city. It can also negate the positive impact of the ocean. The presence of pervious surfaces are important (see section 4.5; 5). LCZB and LCZD as an sub-class as opposed to LCZE - which has become the norm for current developments - can be utilised.

b. Major North/South artery precincts

The North South vehicular arteries that connect the city dominate the form of the city of Colombo. Of these, the Galle Road, the Baseline Road and the Marine Drive are prominent. The Duplication Road and the Havelock Road are the other significant streets. (Fig - 79, 81, 82, 83)

The research highlights the advantage of tall buildings on the edge of urban blocks. (see section 4.5; 7, 8)

The critical aspect of the strategies adopted need to encompass reducing the SVF throughout the length of the vehicular arteries. (see section 4.5; 4, 8)

i. *Perimeter urban block concept for tall, shade providing buildings on edges and open spaces within the interior of the blocks.*

Unlike the Sea Front precinct, tall buildings on edges of urban blocks become advantageous. Yet, it needs to follow the precautions highlighted, where the permeability of the edge is important. LCZ2, LCZ5 with a mix of LCZ3, LCZ4 and LCZ5 of the built types; LCZB and LCZD of land cover types can be advantageous.

ii. *Shading for wide streets to ameliorate the negative effects of extensive impervious surfaces.*

Setbacks and the nature of the street edges for maximum, street level shading

iii. *Maximum permeable surfaces and vegetation cover on edges and the centre island of the street.*

As defined in the Sea front Precinct

c. Major East/West artery precincts

The East/West arteries are seen as critical in creating a connection to the coast and other prominent open spaces in the city. They form the important breaks in the built fabric that has developed along the North/South arteries. Unlike the North/South arteries in the city, these streets are not as continuous and the connection to the coast is not always clear. [see Chapter 4.5 (4)]

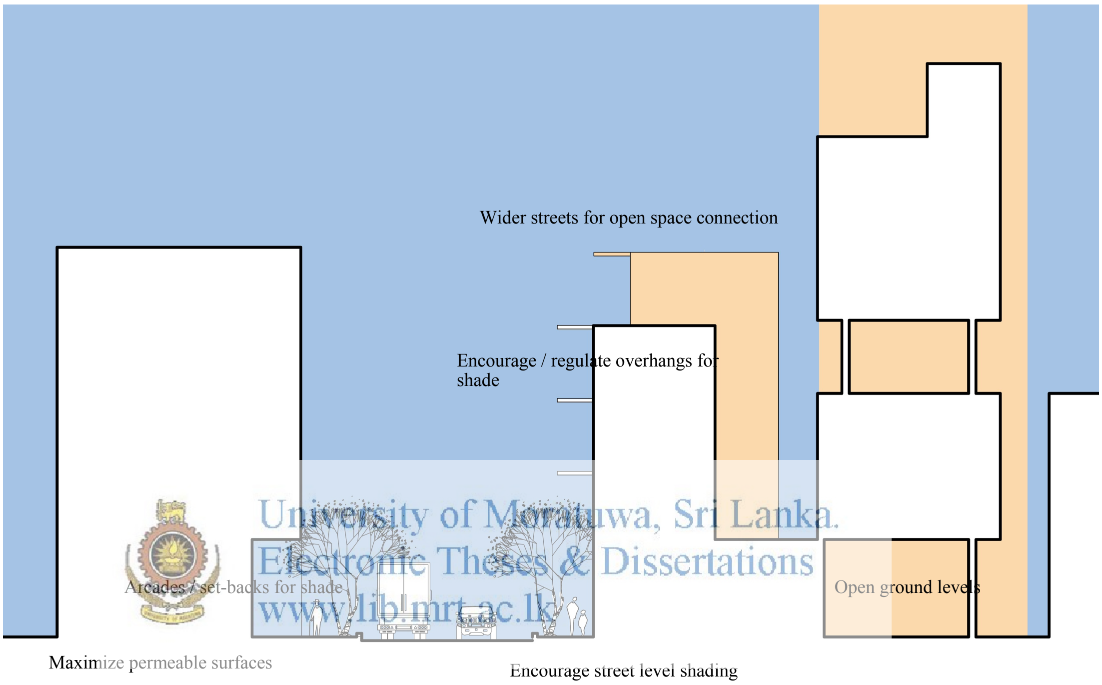


Fig. 84 - Conceptual East/West Artery Section, Colombo

The existence of East/West streets that connect the major North/South arteries highlighted in the earlier section offer a good opportunity for them to be developed effectively. (Fig. 84)

i. *Street widths and setbacks to achieve maximum shading and open space connections*

ii. *Maximum permeable surfaces and vegetation cover on edges and the centre island of the street.*

As defined in the Sea front Precinct

d. <u>Open space precincts - Beira Lake, Viharamahadevi Park, cemetery/golf course precincts</u>

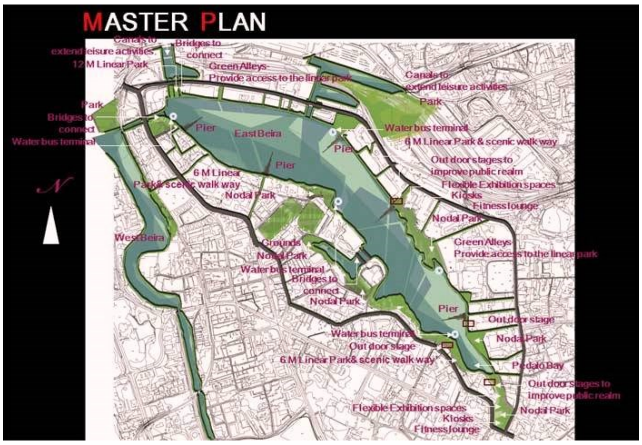


Fig. 85- Biera Lake - Master Plan Proposal.
Source - defence.lk

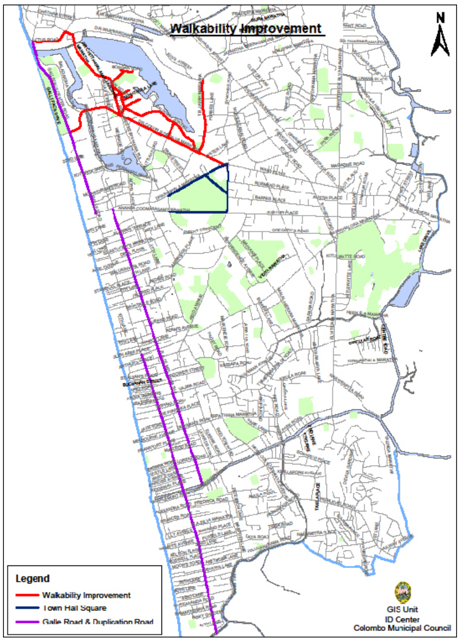


Fig. 86 - Colombo Walkability Improvement Proposal.
Source - cmc.lk

The key open spaces in the city are already the focus of development plans. The current master plans highlight low density, green belt development and increased public spaces as strategies. The LCZ mapping of Colombo also show that these areas are primarily compact, open-set and large low-rise. (LCZ3, LCZ6, LCZ8 of the built types and LCZA, LCZB and LCZD for the land cover types) (Fig 3.8 & 3.9)

The Metro Colombo Urban Development Project is cited as an example. Fig. 85 and Fig. 86 show public space improvement around key areas of the city.
In a city scale climatic perspective, these constitute the key natural, open areas of the city and therefore, the heat sinks that can help ameliorate the ill effects of the UHI phenomenon. [see Chapter 4.5 (6)]

i. Connecting with major arteries and open spaces in the city (Fig. 79)

These can be existing and proposed roads, waterways, railway reservations.

ii. Increasing / maintaining high permeable surface cover in the precinct

As with earlier section (b) the general morphology of the zones can be established as particular LCZs. The uniqueness of the particular precincts in their relationship to open areas and orientation of the public spaces could be controlled by the variables within the ranges defined by the LCZ classification, as LCZ and precinct specific planning and building regulations.

As enhancements to the UDA plans shown in Fig. 85, 86; proposals presented in Fig. 81, Fig. 82 and Fig. 83, especially in relation to the nature of the street edge is conceptualised as essential in its attempt to create climate sensitive public spaces.

5.1.2. Density Regulations

UDA plans for Colombo in 1999 defined building density parameters to guide the scale of the built fabric and the intensity of activities within a particular zone, primarily based on the maximum and minimum heights of a possible development. It also utilised BSF and FAR to regulate. The 2008 amendment, shifted focus to a strategy based on FAR. Yet, the density regulations are not zone specific as seen in the earlier plan. The exception to the above is seen in selected zones (special primary residential and sea front zone for example) where minimum plot extent and coverage has been defined for sub-divisions of land after 2008.

- Density control using urban block or precinct based density criteria, based on LCZ zoning. (see Table 10)
- SVF as the primary defining variable in a LCZ based zoning. [see Chapter 4.5 (4)](Fig. 88, Fig. 89)
- Within particular blocks, it is important to establish density and density boundaries according to orientation and aspect ratio. [see Chapter 4.5 (7, 8)] (Fig. 88, Fig. 89)

As highlighted in the preceding section, a city zoned as precincts of specific LCZs and therefore zoned in a climate sensitive manner, needs to adopt detailed approaches for specific blocks. Although, this is regarded as a departure from the

Within particular blocks, establish density and density boundaries according to orientation and aspect ratio

Taller blocks on edge, creating shade. Lower SVF

Orientation of block matters

Overall LCZ typology remains LCZ2

Encourages a heterogeneous fabric ensuring open space connection

Use SVF as the primary defining variable in a LCZ based zoning - higher edge with lower more pervious center of the block encouraging shade yet night-time radiation loss

Fig. 87 - Conceptual Precinct / Urban block specific density control option visualisation. (example drawn from 'High Edge Option of the simulation series)

Fig. 88 - Conceptual Precinct / Urban block specific density control option visualisation. (example drawn from ’Shadow Umbrella” Option of the simulation series)

simplified approach to classifying the urban fabric; it is deemed necessary to incorporate a particular city context.

This raises the question, how urban planners and designers will incorporate the social and economic needs and priorities of the city together with such a strategy. As highlighted in the zoning implications discussed, the suggested climate sensitivity requirements, existing city structure, and zoning approaches correspond in many aspects. Therefore, the introduction of strategies can adopt a similar approach, familiar to both planners and implementing agencies.

The LCZ system incorporates the probable type of land use, activity zone in general in its categorisation, together with insight into anthropogenic activity that can affect a zone. (see Appendix B) The simplification and categorisation process therefore, include consideration of such socio-economic perspectives. Similarly, in looking at a future scenario, designers can use this adopted process to predict the climatic effects of a development driven by socio-economic needs. The key parameters / variables that research adopts are particular to both climatically and socio-economically driven processes. (see Table 13 and Appendix B)

Value ranges of geometric and surface cover properties for LCZs, developed by Stewart (2012) allow the needed flexibility to achieve the above. (see Appendix B)

LCZ classification system also adopts a final step where the primary LCZ classes are sub-categorised for greater applicability. As seen in Table 10 in Chapter 3, these sub-categorisations have an impact on local level warming. Thus, is deemed an approach to develop more specialised zone specific density controls.

The 'shadow umbrella' approach is a good example, where the block shape is consciously modified in reaction to the orientation of the constituent parts of the block. It also considers functional use categorisation as well. This is highlighted in the research findings, where, 'Within site variations are clear in terms of orientation and aspect ratio'. (Fig.88)

5.1.3. Building Regulations

The current building regulations focus on the space around buildings for individual plots of land. The specification for development (tabulated as Form C in 1999, Form C1 and C2 in 2008) (Appendix A) encompass;

- Minimum land extent
- Minimum width between building lines of a public Street/Road
- Minimum width of private Street/Road
- Maximum permissible FAR

Form C2 of 2008, further define the following according to the building type (low-rise, mid-rise etc.) and the number of floors.

- Minimum site frontage
- Maximum Plot coverage
- Open space around the building
- Minimum Rear space
- Minimum one side space
- Minimum space on each side

The 2008 amendment to UDA building regulations are for individual plots, zone specific regulations are limited to minimum land extent (special primary residential, sea front zone), maximum plot coverage (sea front zone) and maximum building height (special primary residential) for specific zones. (Fig 3.3) Other zones adopt Form C1 and C2 as common regulations.

Here, as the research highlights the need for zone wise interventions, the regulations or its implementation strategy the 'Form C' would also be for a block or a LCZ precinct.

The primary objective of these regulations should be to reduce overall MRT by exploring within site variations in terms of SVF, orientation and aspect ratio.

Define SVF, FAR, HRE, BSF to control / establish block maximum as per LCZ, rather than common regulations.

Canyon geometry is seen as key to managing the MRT intensity in streets. The current regulations adopt 'street lines' and 'building lines' to control the width of the street. (Appendix A). The existing regulations govern individual plots. An approach precinct scale intervention can establish / relax 'building line' regulations for streets of specific orientations within the considered zone.

Greater flexibility within urban blocks to will allow taller buildings on the edges (see Chapter 4.5; 7) and plot specific decision making in terms of open spaces around individual buildings. (rear space, side space to be re-defined as overall open space within a building)

Adoption of SVF based regulations for specific zones. (e.g. sea front precinct - east/west streets need to maximize connection to open spaces. Major North/ South artery precinct - maximize street shading)

Exploring a revisit to the 'standard light plane ' option of old.

The 'standard light plane' was a strategy for lighting and ventilation of buildings adopted in the 1986 building regulations. (Gazette of Democratic Socialist Republic of Sri Lanka Extraordinary No 392/9 of 10th March 1986). The regulations still control development many parts of island outside Colombo and is the precursor to the 1999 and 2008 UDA regulations. The ‘standard light plane’ means a plane drawn upwards and outwards from the exterior face of the building at the lowest floor level of the room at an angle of 63 ½ degrees to the horizontal and not impinging on any building wall or other obstruction. (UDA, 1986). The maximum width of a sunshade or eave intersecting the light plane was limited to 1m.

In the context of this research the light plane can be interpreted as relative to SVF. Where the light plane is applied in an individual building plot, the SVF is increased, creating a greater possibility for night-time radiation loss. Daytime overheating is a necessary consideration.

Therefore, as an extension to the preceding point citing plot specific open spaces; (see Fig. 82, Fig. 83 & Fig. 84)

Relaxation of building line, with imposition of the 'standard light plane' regulations for other open spaces. Particularly the 'rear space'. The relaxation can be approached as thresholds, applicable for each distinct LCZ. Thereby, fulfil the need for street level shade and SVF increment for night-time radiation loss as discussed in the preceding discussion.

Surface cover property introduction into zone regulations, should include streets as an integral part of the zone. Thus, create zone level decisions that will define the overall PSF, ISF and GSF particularly in public spaces. Regulation of individual plot level surface characteristics is deemed impractical.

5.1.4. Development Guide plans

UDA development guide plans are defined for special focus areas in the city.

The overall approach to the earlier section derives an approach similar to the development guide plans proposed for a particular area or zone. In this sense, a city zoned as per LCZ classification could encompass particular zones that need to adopt zone specific strategies as well as zones that adopt general strategies for climate sensitive urban spaces. This aspect was discussed at length in preceding sections, therefore deemed ingrained in their proposed guidelines. (Fig. 79)

5.2 Policy implications

5.2.1 Policy implications of a Local Climate Zone based Planning Strategy

The policy implications of achieving the planning strategies discussed in the preceding section is important for overall applicability in an urban context.

Protocols for mapping the urban area using the Local Climate Zone classification system

Precinct / Local scale climate mapping and maps are crucial for strategies / interventions at that particular scale. It is at this scale that outdoor thermal comfort and building level energy use can be influenced for greater effectiveness.

City scale microclimatic measurement regimes or simulation models are intensive in terms of resource, cost and time. Approaches like on site measurements cannot dispel the influence of anthropogenic and material aspects in their focus on particular variables. They cannot look ahead to a globally warmed scenario.

Herein lays the advantage of the Local Climate Zone classification. It is *local* in scale, *climatic* in nature and *zonal* in representation. (Stewart & Oke, 2012)

Observational data is used to quickly and effectively classify the urban context into distinct morphological and climatic zones, which can be compared across cities of similar geographies and climates. It offers a basic package of urban climate principles for architects, planners, ecologists, and engineers. The system conveys these principles through spatial scales (micro, local) and design elements (e.g., building height, "green" cover ratio) that are relevant to the many cognate disciplines of urban climatology. (Stewart & Oke, 2012)

The danger is in the over simplification of the context, especially in using them as planning zones. Stewart and Oke originally developed the scheme primarily for establishing a common protocol for UHI reporting.

The LCZ system is inherently generic and cannot capture the peculiarities of every urban and rural site. Its view of the landscape universe is highly reductionist, and, like all classifications, its descriptive and explanatory powers are limited. (Stewart & Oke, 2012)

<u>Zoning policy for the city to be based on Local Climate Zones - for future development and climatic backgrounds</u>

As highlighted in the earlier sections, LCZ classification incorporates geometric, surface characteristics together with thermal, radiative and metabolic value ranges in their selection.

The adoption of such LCZ based zoning has advantages of implementing city scale interventions that not only have characteristic morphology, but the incorporation of climate characteristics within the selection. It also gives insight into the probable anthropogenic impact of a zone.

The sub-categorisation and within zone definition of properties allow the desired heterogeneity and design flexibility to the fabric. Thus, also maintain the socioeconomic effectiveness in a sustainable urban system.

The ability to use observational data for the LCZ classification in resource poor contexts in a time efficient manner is an added advantage.

The main drawback to the zoning is seen in the next section of the process where zone specific guidelines need to be defined.

<u>Policy on LCZ specific definitions and standards for climate sensitive urban outdoors</u>

The range of values defined within the LCZ system establishes these same criteria as the base value for a particular zone. Therefore, policy standards and technical benchmarks are automatically established.

It is in the interpretation of the value ranges embedded in the LCZ system to the context of a city that creates the most queries. Particularly in establishing zone specific density and building regulations.

LCZ datasets are developed from generalized knowledge of built forms and land cover types that are universally recognized, not from specialized knowledge of local topography and climatology in individual cities. (Stewart & Oke, 2012)

This raises questions as to the effectiveness of the defined value ranges in the urban context of a particular city; it effectiveness for a globally warmed background scenario; the method in which the values, value ranges or benchmarks will be defined, in a specialised zone application; the probability and extent to which sub-categorisation is allowed; and thus, the manner in which the values will change. It is in this area that a problem of equity would arise in terms of which plot (in an urban block that is made up of several individual plots) gets to exceed the zone norms. These issues are discussed in detail in section 5.2.2 in this chapter.

Quantitative design guidelines that practitioners can easily apply in terms of the basic design requirements for sustainable urban public space creation.

These quantitative guidelines can be in the form of simple ratios and indexes as used in a density regulation system at zone scale and the building regulation system at the individual plot scale. This avoids the need for a comprehensive modelling regime for their approval. A more stringent system of evaluation can be adopted for large-scale intervention.

The planning implications were based primarily on the morphological aspects of the context. Relevant constituents pertaining to materiality, urban vegetation and transport were not taken into account.

5.2.2 Policy on socio-economic and governance mechanisms

The challenge of incorporating Planning and Policy approaches presented in the preceding sections are seen primarily with relation to socio-economic and governance perspectives. It is clearly understood that any development strategy, must incorporate these factors for its realisation.

(a) Socio-Economic Impacts

Socio-economic impacts are envisioned at two levels of the urban fabric; at the city scale - where distinctive precincts are defined; and within the precinct - where the built elements (the blocks) and the open spaces (the streets) need consideration.

<u>City-scale intervention- *the Precinct*</u>

As presented in Section 5.2 and Fig. 82, the primary objective was to create precincts of characteristic morphology that adhere to its context.

These precincts ear-marked for LCZ based definition change in their character could freeze current level development and control future intervention in achieving the desired zoning. Thus, not effecting the current socio-economic potential of the precinct. Yet, in some cases, the 'freeing' of current socio-economic status could be problematic (such as, in poorer parts of the city). A variance in the tax regime to encourage potential development to adhere to projected city scale intervention strategies, both for the current climatic background and that of a context warmed by global warming can be encouraged

<u>Precinct-scale intervention</u>

Precinct-scale intervention is approached as two elements of the same scheme, yet defined separately for clarity of discussion. These elements encompass;

- Block shape
- Street shape

Block shape

Zoning of precincts are approached with an urban block as its core module. The urban block also becomes the unit in classifying LCZs. Therefore, a scheme that is based on the same element for classification, definition and implementation is deemed more effective.

Most zoning and building regulations use building plot extent and street characteristics to control. Here the emphasis on the total urban block, therefore, creates queries as to – How? - equitable development can be facilitated.

A LCZ-based methodology is based on thresholds of the key LCZ Parameters and therefore is more flexible than a n approach based on individual plots/streets. This approach could therefore offer room for the preservation of current socio-economic positives of the neighbourhood, provided these thresholds are not exceeded.

This flexibility allows shaping of the block to create more climate sensitive in-between spaces. It also allows for flexibility in the extent and way building can occur within a specific block. To create socio-economic equity an incentive and / or tax based approach can be encouraged to maintain overall block shape, while infusing heterogeneity within the parameters. (e.g. utility rate surcharge for non-compliance or vice-versa). A better defined implementation scheme to accommodate and evaluate the flexible options of the intervention will need to be developed hand-in-hand, given the complexity as opposed to known, conventional mechanism.

Street shape

The 'Street' or 'Public space' between buildings are deemed crucial at all levels for climate sensitive shaping of the city. The shape of the urban canyon influences both the block (due to its edges that abut the street) and overall city form.

A similar incentive / tax based scheme presented above, can be encouraged for adhering to defined street shape / canyon geometry. Such an approach can be extended to encompass varied street orientations. (e.g. north/south east facing streets vs. north/south west facing streets)

(b) Governance Mechanism

The section discusses the Governance Mechanism for implementing the LCZ based planning and policy for climate sensitive urban public spaces. It is approached as a cyclic and therefore, continually developing methodology for greater applicability and equity.

Suggested governance mechanism is taken in stages, outlined below;

- Planning and Policy Stage
- Design and Compliance Stage
- Monitoring Stage

Planning and Policy stage

The LCZ classification system forms the base of the decision making process. Planning and Policy for a particular city is envisioned as a mechanism for amelioration of the existing context as well as a means of projecting urban fabric morphology characteristics of a city for the future.

It is important to establish LCZ based planning and policy guidelines as mandatory and / or prescriptive means of developing the climate sensitive city form. It needs to be based on specific information encompassing; local expertise, existing fabric, geographical and climatic nuances in establishing goals for future form and development needs

Ensuring maximum access to information is crucial for success. These can take the form of accessible maps for all stakeholders. (Planners, designers, developers, citizens, residents etc.); digital data-bases (e.g. Geo-Wiki) encompassing data layers for urban scale and building scale intervention / adherence; and an option matrix that drives decision making by the city and individuals

Design and Compliance Stage

The design and compliance stage is deemed pivotal for the process, especially in terms of decision making and resource utilisation. As stated in the preceding section, the availability of information resources and compliance guidelines are important. The approach can be - once all stakeholders are agreed (at the Planning and Policy Stage) on the acceptable thresholds of key LCZ variables, these will provide an open and transparent basis for checking compliance

Information resources can be in the form of an established database of readily accessible, detailed maps projecting the planning and policy of the local level administration; an empowering of local level approval agencies with needed human resources to guide development initiatives; a comprehensive rating matrix of urban parameters to aid decision making. (e.g. (CASBEE 2013))

Compliance information that encompass established LCZ based norms as checklist for compliance and decision making; precinct specific values ranges to allow flexibility of design options; established and therefore clear socio-economic decision making options. (e.g. owner pays or city compensates schemes); a checklist of submissions for evaluation at both urban and building scale. (e.g. microclimatic impact, anthropogenic impact etc.) can drive better decision making at the design stage.

Monitoring Stage

The monitoring stage will ensure the planned, climate sensitive city to be monitored for its success and / or failures. The primary advantage of the LCZ based scheme is highlighted here. Where, the morphology based application and adherence protocol allows quick evaluation of a particular situation.

To achieve this a continually updated / maintained digital database (as mentioned in the preceding planning and policy stage) of city characteristics, together with a monitoring network for microclimate impacts of envisioned planning intervention can be utilised. It needs to include socio-economic data feedback, thus establish possibilities for fine tuning of the approach.

Summary

The chapter addresses the third research question of the thesis, encompassing the approaches to link the findings into planning and policy.

The primary mode to do this was the Local Climate Zone system and the sensitivity of parameters for the amelioration of UHI and the creation of climate sensitive public spaces.

While the planning discussion drew upon the city of Colombo as a case study of utilisation, the policy component attempts to build a more generalised approach that can be easily adopted similar climate / morphology cities. The discussion also extends to socio-economic conditionalities that create a more equitable and just urban planning policy.

6.0 Conclusions

The thesis explored avenues for achieving the aim of "**Bridging the gap in urban design-climate links, being translated into guidelines for real-world applicability** in a background climate affected by **Global Warming.**

The study was focussed on the **warm humid tropical** climate of **Colombo**, **Sri Lanka -** as an experimental context for the research.

This chapter brings together the summary of findings, summary of contributions, methodological challenges and directions for future research.

6.1 Summary of findings

In the opening chapters of the thesis, research gaps were identified based on the literature review generating three main questions in formulating a methodology to approach the primary aim of the research. The summary of findings for each question individually, is presented as a summary of detailed analysis and discussion covered in the preceding chapters.

1. What is the microclimatic background condition that climate sensitive urban policy needs to be based upon?

The primary methodological approach to the question utilised observational data to map Local Climate Zones in Colombo.

- It is shown that the City of Colombo, Sri Lanka, is a warm, humid city affected by Urban Heat Island, with intensities up to 4.40 ^{o}C over the 'rural' site selected.
- The city context is dominated by LCZ3 - Compact low-rise, LCZ2 - compact mid-rise and LCZ8 - Large low-rise.
- Results and analysis reveal that almost all LCZ zone changes from a lower density classification to a high density classification, push the UHI intensity to a higher level than the existing.

2. **What are the key urban morphology variables (Geometric and Surface Cover) that will define and drive the decision making process, at both the existing as well as a warmed urban microclimate?**

Sensitivity analysis of what are key design parameters for the mitigation of UHI and Outdoor Thermal Comfort in the tropics were based on the simulation of existing and projected urban fabric morphology in background climatic contexts of both existing and a future warmed scenario (warmer by 2.40 ^{o}C in the year 2100). The simulation uses the tool ENVI-met and adopts MRT as the dependent variable in a series of cases for analysis.

Specific patterns highlighted across the case study series;

1. In general, night-time shows better correlation with MRT
2. The rate at which MRT changes for the hours that the microclimate rapidly warms and cools during the day show little or no variation between cases.
3. Among specific cases, case4 - green global warming scenario shows stronger correlation of variables with that of MRT.

4. The Sky View Factor (SVF) shows the strongest correlation to MRT.
5. The characteristics of the surface cover in general and 'green' surface cover in particular, has little or no effect in reducing the MRT intensity in the urban outdoors.
6. Overall context to Individual site correlation characteristics do not show a distinct pattern.
7. In general, taller buildings at the edges of urban blocks have a positive impact.
8. Within urban blocks, variations are clear in terms of orientation and canyon geometry.

3. **What are the planning and policy implications that can be generated to adapt to or roll-back the negative effects of a warmed urban microclimate?**

The approach to question 3 is a conversion of findings into planning and policy, with Colombo as the experimental focus of the discussion. The main emphasis is on a protocol that deploys a LCZ based approach for climate sensitive urban design in data scarce tropics.

The discussion on planning implications was based on LCZs as planning precincts on the city scale and was detailed down to density and building regulation thresholds of a urban block within an overall approach to climate sensitive public spaces.

Policy implications brought together the salient factors for a LCZ based planning strategy and its approach to socio-economic and governance perspectives for a sustainable approach to UHI mitigation and climate-sensitive urban space.

6.2 Summary of Contributions

Theoretical Contribution

The theoretical contribution of the thesis is the conceptual framework, based on which the study of urban design - climate links are explored. It establishes a protocol that can be generalised in its application in seeking the relationship between global warming and local warming in general and climate sensitive urban design in particular.

The frame work, based on three questions, apply to all stages in a protocol for achieving the needed outcomes of a climate sensitive approach to urban development. The questions transform into specific areas of emphasis in research, synthesis and application stages of a design approach.

The pivotal component of the conceptual framework is the Local Climate Zone classification system.

The overwhelming advantage of the 'Local Climate Zone' based strategy is that the LCZ 'classes are local in scale, climatic in nature, and zonal in its representation' (Stewart & Oke, 2012), encompasses a protocol that can be rapidly mapped and yet be comparable across similar urban contexts. The benefit of such a system for data-scarce developing cities is emphasised.

Empirical and Policy Contributions

The thesis advances the study of urban design-climate links through the following contributions;

1. ***Mapping of "Local Climate Zones" and relative Warming Effects in Colombo, Sri Lanka***

   The classification of urban field sites into LCZs, utilising the 'urban block' as the core component offered possibilities for the rapid mapping of urban contexts in relation to both climate and urban morphology in data-scarce tropical cities. The use of observational data enabled a quick yet relevant classification of the city context and therefore allowed further application studies to be based upon the mapping.

   The analysis of the LCZ map of Colombo in terms of UHI and UHI intensity as a comparison between local climate zoning reveals the effect of urban morphology on local level warming. Therefore, establishes the basis for climate sensitive application and future research.

2. ***Sensitivity analysis of what are the key design parameters for the mitigation of UHI and Outdoor Thermal Comfort in the tropics.***

   The LCZ classification system encompasses critical urban parameters in their definition. A sensitivity analysis focussed on Geometric and Surface Cover characteristics, together with climatic parameters allows an in-depth understanding of which parameters are critical in an approach to create climate sensitive urban public spaces. The sensitivity of the parameters are explored as applicable in existing climatic contexts as well as in a context that has been warmed by the negative effects of global warming.

The analysis employing a series of morphology options extend the level of understanding of which parameters matter most in the attempt to formulate planning and policy in creating a climate sensitive city.

3. *A "Local Climate Zone" based approach to Climate-Sensitive Planning and Policy in the Warm Humid Climate of Colombo, Sri Lanka*

Planning

The thesis presents a conceptual yet comprehensive set of guidelines for UHI mitigation in a tropical city. The guidelines encompass; Zoning Plan and Planning regulations; Density regulations; Building regulations; Development guide plans in its attempt to be compatible to the existing development projections by the Urban Development Authority for Colombo, utilised as the experimental context for application and discussion.

The primary component of the planning approach is the zoning of the city's urban context as precincts defined according to the LCZ typology classification. The characteristics within a defined LCZ precinct / urban block allow for the specific definition of density and building regulations.

Policy

Policy recommendations are presented as two components; Policy implications of a Local Climate Zone based Planning Strategy and Policy on socio-economic and governance mechanisms.

Policy implications focus on the means of incorporating the envisioned conceptual planning strategies into the decision making process in the future development of the city. The main advantage of the policy recommendations is a protocol for rapid evaluation, application and monitoring in a data-scarce tropical city.

6.3 Methodological Challenges and Future Research

Limitations and Methodological challenges

The methods and techniques used in this thesis have yielded satisfactory results, reinforced by the fact that the findings adhere to established knowledge in tropical climates.

In reference to the limitations stated in chapter 1;

- The study is limited to the hot **warm humid city** of Colombo, Sri Lanka.
- The focus is on climate sensitive urban public space, therefore the research is limited to the urban canopy layer. It analyses the causes and effects of changing morphology at a 1.5m height above the ground, termed street level. The height that a person on the street would perceive the environment.
- Local climate mapping to ascertain the critical ' Local Climate Zones' in Colombo, are simulated for conditions of calm and clear skies.
- The study was carried out for a particular day in April (simulation date 15.04.2013), since this month is deemed the most critical time of the year and therefore the worst case scenario to be designed for.

The main methodological limitations are seen in the simplification of the urban morphology, the simulation and the limitation of the simulation period. Each of these aspects are discussed at length in the respective sections in Chapter 3 - Research Design.

Avenues for Future Research

The main avenues for future research are seen in the widening of the scope of the current research.

- Develop contextually validated MRT / PET thresholds for thermal acceptability / preference specifically for Colombo.
- Simulation and analysis for the complete range of Local Climate Zones, across varied cities typologies in Sri Lanka.
- A widening of the scope of urban morphology options, fuelled by a more comprehensive look at the shadow umbrella concept.
- The inclusion of urban vegetation in the method, thereby encompass an analysis protocol involving not only SVF created by buildings, but rather both buildings and trees.
- An exploration of the materiality aspects of the urban fabric.
- Options for combining LCZ with other social and economic priorities

Further, the data generated in the current research can contribute to several future studies;

- The effect on local level wind movement, within simulated morphology patterns
- Mean Radiant Temperature patterns at different heights above the street, and its relationship to energy use in buildings. MRT cross sections across critical urban canyon geometries.
- Shadow patterns created in the urban outdoors and potentials for public space design.
- The effect of shading on Daylight Integration in buildings.

6.4 Conclusion

The thesis contributes to the primary aim of"- "**Bridging the gap in urban design-climate links, being translated into guidelines for real-world applicability** in a background climate affected by **Global Warming** - by presenting a conceptual framework for achieving these outcome, based on the Local Climate Zone classification system.

The contributions and recommendations for - a Local Climate Zone based - planning and policy offer an approach to ameliorate the negative effects global warming, the urban heat island and outdoor thermal comfort in a holistic and sustainable design approach for the creation of climate sensitive city contexts in general and public spaces in particular.

References

Acero, J., Boettle, M., Costa, L., Gudipudi, R., Holsten, A., Kropp, J. P., Walther, C. (2014). WP 2: Taxonomy of Architecture and Infrastructure Indicators Physical and cost typology for buildings and infrastructure / project database (Vol. 308497).

Ahmed K. S. (2003). Comfort in urban spaces: defining the boundaries of outdoor thermal comfort for the tropical urban environments, Energy and Buildings. 35, pp. 103-110

Alcoforado, M.-J. (2006). Planning Procedures towards High Climatic Quality Cities. Example referring to Lisbon. Finisterra, XLI (82), 49–64.

Ali-Toudert, F (2005) Dependence of Outdoor Thermal Comfort on Street Design in Hot and Dry Climate. (Doctoral Thesis) Department of Meteorology and Climatology Albert-Ludwig-University of Freiburg. p. 224

Ali-Toudert, F., & Mayer, H. (2006). Numerical study on the effects of aspect ratio and orientation of an urban street canyon on outdoor thermal comfort in hot and dry climate. Building and Environment, 41(2), 94–108. doi:10.1016/ j.buildenv.2005.01.013

Balogun, I. A., Balogun, A. A., & Adeyewa, Z. D. (2012). Structure of urban heat island and sky view conditions in Akure, Nigeria. In ICUC8 – 8th International Conference on Urban Climates. Dublin, Ireland.

Basnayake, S. (2004). Impacts & Adaptation to Climate Change A Sri Lankan Perspective. In Second International Conference on Climate Impacts Assessment. Grainau, Germany.

Baumüller, J., Hoffmann, U., & Reuter, U. (1992). Climate booklet for urban development, Ministry of Economy Baden-Wuerttemberg, Environmental Protection Department. http://www.staedtebauliche-klimafibel.de

Bechtel, B., Daneke, C., Langkamp, T., Oßenbrügge, J., & Böhner, J. (2012). Classification of Local Climate Zones from multitemporal remote sensing data. In ICUC8 – 8th International Conference on Urban Climates. Dublin, Ireland.

Black, A. L. (2013). Temperature Trends and Urban Heat Island Intensity Mapping of the Las Vegas Valley. (Masters Thesis) University of Nevada, Las Vegas.

Brazel, A. J., & Crewe, K. (2002). Preliminary Test of a Surface Heat Island Model (SHIM) and Implications for a Desert Urban Environment, Phoenix, Arizona. Journal of the Arizona-Nevada Academy of Science, 0104(2), 98–105.

Carfan, A. C., & Galvani, E. (2012). Study of thermal comfort in the City of São Paulo using ENVI -met model, 34–47.

Carfan, A. C., Galvani, E., & Nery, J. T. (2012). Study of the microclimate effect in the urban vertical structure in Ourinhos, São Paulo State, 313–320. doi:10.4025/actascitechnol.v34i3.12322

Carr, S., Francis, M., Rivlin, L. G., Stone A. M. (1992). Public Space. Cambridge University Press

Chok, N. S. (2010). Pearson's Versus Spearman's and Kendall's Correlation Coefficients for Continuous Data. (Masters Thesis) University of Pittsburgh.

Criterion Planners. (2014). A Global Survey of Urban Sustainability Rating Tools. Portland, Oregon. Retrieved from http://crit.com/wp-content/uploads/2014/11

Dubois, C., Bergeron, O., Potvin, A., & Adolphe, L. (2012). Adapting cities to climate change: heat and urban form. In ICUC8 – 8th International Conference on Urban Climates. Dublin, Ireland.

Economic Modelling Specialists Inc. (2007) Understanding Location Quotient. Retrieved from http://www.economicmodeling.com/wp-ontent/uploads/2007

Eliasson, I., Knez, I., Westerberg, U., Thorsson, S., & Lindberg, F. (2007). Climate and behaviour in a Nordic city. Landscape and Urban Planning, 82(1-2), 72–84. doi:10.1016/j.landurbplan.2007.01.020

Emmanuel, R. (1993). A Hypothetical "Shadow Umbrella" For Thermal Comfort Enhancement in the Equatorial Urban Outdoors. Architectural Science Review.

Emmanuel, R. (2004). Historic thermal comfort trends induced by urbanization in Colombo, Sri Lanka. In PLEA2004 – The 21st Conference on Passive and Low Energy Architecture (pp. 19–22). Eindhoven, The Netherlands.

Emmanuel, R. (2005). An Urban Approach to Climate-sensitive Design: Strategies for the Tropics (First Edit., p. 172). Taylor & Francis.

Emmanuel, R. (2010). Linking the "In" And "Out:" New Comfort Goals for the Rapidly Urbanising Equatorial Tropical Megacities in a Changing Climate. In Adapting To Change: New Thinking on Comfort, Network for Comfort and Energy Use in Buildings. UK

Emmanuel, R. (2011). Urban Heat Islands and sustainable urbanity: An application agenda for tropical mega-cities. In City Weathers: Meteorology and Urban Design 1950-2010 Manchester (pp. 23–24).

Emmanuel, R., & Fernando, H. (2007). Urban heat islands in humid and arid climates: role of urban form and thermal properties in Colombo, Sri Lanka and Phoenix, USA. Climate Research, 34(3), 241–251. Doi: 10.3354/cr00694

Emmanuel, R., & Johansson, E. (2006). Influence of urban morphology and sea breeze on hot humid microclimate: the case of Colombo, Sri Lanka. Climate Research, 30(3), 189–200. Doi: 10.3354/cr030189

Emmanuel, R., Drach, P., & Kruger, E. (2012). 213: UHI studies for low carbon cities: integrating heat mapping with morphological attributes. In ICUC8 – 8th International Conference on Urban Climates. Dublin, Ireland.

Emmanuel, R., Perera, N. G. R., & Madhuwanthi, H. (2011). Mitigating Urban Warming as an Adaptation Strategy to Climate Change in the Warm, humid tropics. In review.

Emmanuel, R., Rosenlund, H., & Johansson, E. (2007). Urban shading - a design option for the tropics? A study in Colombo, Sri Lanka. International Journal of Climatology, 27(14), 1995–2004. doi:10.1002/joc.1609

Erell, E., Pearlmutter, D., & Boneh, D. (2012). 236: Effect of high-albedo materials on pedestrian thermal comfort in urban canyons. In ICUC8 – 8th International Conference on Urban Climates. Dublin, Ireland.

Eriyagama, N.; Smakhtin, V.; Chandrapala, L.; Fernando, K. 2010. Impacts of climate change on water resources and agriculture in Sri Lanka: a review and preliminary vulnerability mapping. Colombo, Sri Lanka: International Water Management Institute. 51p. (IWMI Research Report 135). doi:10.3910/2010.211.

Fahmy, M., & Sharples, S. (2008). Passive design for urban thermal comfort: a comparison between different urban forms in Cairo, Egypt. In PLEA 2008 – 25th Conference on Passive and Low Energy Architecture. Dublin, Ireland.

Francisco, R. C. A., Assis, E. S. De, & Assunção, M. (2012). Calibrating the model ENVI-Met for the city of Bela Horizonte. (Masters Thesis – Abstract) Federal University of Minas Gerais, Brazil

Fröhlich, D., Matzarakis, A. (2012). 156: Application of micro scale models for bioclimatic assessment – Examples from Freiburg. In ICUC8 – 8th International Conference on Urban Climates. Dublin, Ireland.

Futcher, J., Millis, G. (2014). The Selfish Giants. CIBSE Journal. Issue 61, pp23

Gazette of Democratic Socialist Republic of Sri Lanka Extraordinary No 392/9 of 10th March 1986 (1986). Urban Development Authority of Sri Lanka.

Georgescu, M., Morefield, P. E., Bierwagen, B. G., & Weaver, C. P. (2014). Urban adaptation can roll back warming of emerging megapolitan regions. In Proceeding of the National Academy of Sciences of the United States of America (pp. 1–6). doi:10.1073/pnas.1322280111

Giridharan, R. (2005). Urban design factors influencing outdoor temperature in high -rise high-density residential developments in the coastal zone of Hong Kong. The University of Hong Kong. http://hdl.handle.net/10722/40965

Givoni, B. (1998). Climate considerations in building and urban design. New York: Van Nostrand Reinhold.

Glasgow Caledonian University, Emmanuel, R. (2013). Green Infrastructure for overheating adaptation in Glasgow. In review

Golany, G. S. (1996). Urban design morphology and thermal performance. Atmospheric Environment. 30, p455-465.

Grimmond, C. S. B. S. B., Roth, M., Oke, T. R. R., Au, Y. C. C., Best, M., Betts, R., Voogt, J. (2010). Climate and More Sustainable Cities: Climate Information for Improved Planning and Management of Cities (Producers/ Capabilities Perspective). Procedia Environmental Sciences, 1, 247–274. doi:10.1016/j.proenv.2010.09.016

Grimmond, C. S. B. S. B. (2013). Observing London: Weather data needed for London to thrive. Retrieved from http://climatelondon.org.uk/wp-content/uploads/2013/07

Gunaratna, K. L. (2012). Colombo’s' Growth : Thoughts on Its Emerging Future: Thoughts on its Emerging Future. In Faculty of Architecture Research Unit. International Research Symposium 2012 – University of Moratuwa, Sri Lanka.

Hebbert, M. (2014). Urban Climate Climatology for city planning in historical perspective. Urban Climate, In-Press

Hung T, Uchihama D, Ochi S, Yasuoka Y. (2006). Assessment with satellite data of the urban heat island effects in Asian mega cities, International Journal of Applied Earth Observation and Geoinformation, 8, pp. 34–48

Hwang R.-L, Lin T.-P, Matzarakis A. (2011). Seasonal effects of urban street shading on long-term outdoor thermal comfort. Building and Environment. 46, pp. 863–870

IPCC. (2007). Climate Change 2007 : Synthesis Report XXVII (pp. 12–17).

Japan International Coorporation Agency. (2014). Urban Transport System Development Project. Colombo. Retrieved from http://www.transport.gov.lk/web/images/stories/F-CoMTrans_Main_S.pdf

Jauregui E. (1993). Bibliography of Urban Climate in Tropical/ Subtropical Areas, 1981–1991, WCASP-25, WMO/TD-No. 552. World Meteorological Organisation: Geneva; 87

Jauregui E. (1996). Bibliography of Urban Climatology for the Period 1992–1995 Including a Special Section on Urban Climate in Tropical/Subtropical Areas, WCASP-36, WMO/TD-No. 759. World Meteorological Organisation: Geneva

Johansson, E., Spangenberg, J., Gouvêae, M. L., & Freitas, E. D. (2013). Scale-integrated atmospheric simulations to assess thermal comfort in different urban tissues in the warm humid summer of São Paulo, Brazil. Urban Climate, 24–43.

Kataoka K, Matsumoto F, Ichinose T, Taniguchi M. (2009). Urban warming trends in several large Asian cities over the last 100 years". Sci. Tot. Environ. 407, pp. 3112-3119. doi: 10.1016/j.scitotenv.2008.09.015.

Kaveckis, G., & Bechtel, B. (2014). Land Use Based Urban Vulnerability to Climate Change Assessment. In The 9th International Conference "Environmental Engineering." Vilnius, Lithuania: Vilnius Gediminas Technical University 2014. doi:10.3846/enviro.2014.122

Knez I, Thorsson S, Eliasson I, and Lindberg F, (2009) "Psychological mechanisms in outdoor place and weather assessment: towards a conceptual model," International Journal of Biometeorology, vol. 53, no. 1, pp. 101–111

Kotthaus, S. & Grimmond, C.S.B., (2013) Energy exchange in a dense urban environment – Part II: Impact of spatial heterogeneity of the surface. Urban Climate, pp.1–27.

Kovács, A. & Németh, A, (2012) Tendencies and Differences in Human Thermal Comfort in Distinct Urban Areas in Budapest, Hungary. Acta Climatologica et Chorologica, Pp.115–124.

Lim, H. V. (2014). Measuring and Modelling Spatial Variation of Temperature and Thermal Comfort in a Low-Density Neighbourhood in Singapore. (Masters Thesis) National University of Singapore.

Masson, V., Marchadier, C., Adolphe, L., Aguejdad, R., Avner, P., Bonhomme, M., Zibouche, K. (2014). Adapting cities to climate change: A systemic modelling approach. Urban Climate, 10, 407–429. doi:10.1016/j.uclim.2014.03.004. In Press

Mayer H. (1993) Urban bioclimatology. Experientia 49: 957–963. DOI:10.1007/BF02125642

Mayer, H., Höppe, P. (1987) Thermal comfort of man in different urban environments. Theoretical and Applied Climatology 38: 43–49.

McCarthy, M. P., Best, M. J., & Betts, R. (2010). Climate change in cities due to global warming and urban effects. Geophysical Research Letters, 37(9), doi:10.1029/2010GL042845

Middel, A., Häb, K., Brazel, A. J., & Martin, C. (2012). 394: Urban form, landscape design, and microclimate in Phoenix, Arizona. In ICUC8 – 8th International Conference on Urban Climates. Dublin, Ireland.

Milgram S. (1970). The Experience of Living in Cities. Science, New Series, Vol. 167, No. 3924, pp. 1461-1468 American Association for the Advancement of Science

Mills, G., (1999). Urban Climatology and Urban Design. ICUC, International Conference on Urban Climatology in Sydney, Australia, 8–12 November. Extended abstracts.

Mills, G. (2004). Urban Climate, Weather and Sustainability. The State of the Planet: Frontiers and Challenges in Geophysics. Geophysical Monograph 150, IUGG, 19. Doi: 10.1029/150GM31

Mills, G. (2006) Progress toward sustainable settlements : a role for urban climatology. Energy and Buildings, 76, 69–76. Doi: 10.1007/s00704-005-0145-0

Mills, G. (2007). Cities as agents of global change. International Journal of Climatology, 1857(August), 1849–1857. Doi: 10.1002/joc

Mills, G., Cleugh, H., Emmanuel, R., Endlicher, W., Erell, E., McGranahan, G., & Ng, E. (2010). Climate Information for Improved Planning and Management of Mega Cities (Needs Perspective), 1, 228–246. doi:10.1016/j.proenv.2010.09.015

Mills, G. (2011). Urban Scales & Effects. In Urban Climatology for Tropical & Sub-tropical Regions Croucher Advanced Study Institute 2011-2012.

Munasinghe, G. (2013). Colombo Development Plan History. Retrieved October 05, 2014, from http://townplanninginsrilanka.blogspot.com/2013/02/colombo-development-plan-history.html

NCSS Statistical Software. Stepwise Regression. Retrieved from http://www.ncss.com/wp-content/themes/ncss/pdf/Procedures/NCSS/Stepwise_Regression

Ng E. (2009). Policies and technical guidelines for urban planning of high-density cities – air ventilation assessment (AVA) of Hong Kong. Building and Environment. 44, pp. 1478–1488

Ng, E. Chen. V (2006). Thermal comfort in urban open spaces for Hong Kong. Architecture Science Review, 49.3, 236–242.

Nieuwolt, S. (1966). The urban microclimate of Singapore. Journal of Tropical Geography. 22, pp. 30-37

Oke, T. R. (1997) Surface climate processes. In: Bailey WG, Oke TR, Rouse WR (Eds.) Surface climates of Canada. Montreal: McGill-Queen's University Press, pp. 21–43

Oke, T. R. (2006). Towards better scientific communication in urban climate. Theoretical and Applied Climatology 84: 179–190.

Oke, T. R. (1982). The energetic basis of the urban heat island. Quarterly Journal of the Royal Meteorological Society. vol. 108 (455) p. 1-24

Oke, T. R., Kalanda, B. D., & Steyn, D. G. (1981). Parameterization of heat storage in urban areas. Urban Ecology, 5(1), 45–54. Doi: 10.1016/0304-4009(81)90020-6

Oke, T. R. (1987) Boundary Layer Climates, Routledge, London, UK, 2nd edition, Oke, T. R. (2004) “Initial guidance to obtain representative meteorological observation sites,” WMO/TD 1250

Parker, D E. 2010. Urban heat island effects on estimates of observed climate change, WIRES Climate Change, 1, pp. 123–133

Peng, C., & Elwan, A. F. A. (2012). Bridging Outdoor and Indoor Environmental Simulation for Assessing and Aiding Sustainable Urban Neighbourhood Design. Archnet-Ijar, International Journal of Architectural Research, 6(3), 72 –90.

Peng, L. L. H., & Jim, C. Y. (2013). Green-Roof Effects on Neighbourhood Microclimate and Human Thermal Sensation. Energies, 6(2), 598–618. Doi: 10.3390/en6020598

Perera, N. G. R., & Weerasekara, W. M. S. B. (2014). The Effect of Street Canyon Geometry on Outdoor Thermal Comfort in Colombo. In 2nd International Conference on Cities, People, Places. Colombo, Sri Lanka

Perera, N. G. R., Emmanuel, M. P. R., & Mahanama, P. K. S. (2012). 576 : Mapping “Local Climate Zones” and relative Warming Effects in Colombo, Sri Lanka. In ICUC8 – 8th International Conference on Urban Climates, Dublin, Ireland.

Perera, N. G. R., Emmanuel, M. P. R., & Mahanama, P. K. S. (2013). Projected urban development, changing “Local Climate Zones” and relative warming effects in Colombo, Sri Lanka. In International Conference on Cities, People, Places. Colombo, Sri Lanka

Priyadarshini R, Wong NH, Cheong KWD. (2008). Microclimatic modelling of the urban thermal environment of Singapore to mitigate urban heat island. Solar Energy. 82, pp. 727–745

Proffitt, D. (2013). A Neighbourhood Scale Model for Understanding Urban Heat Island Effects of New Development. In Salzburg Congress on Urban Planning and Development (SCUPAD) Salzburg, Austria.

Puliafito, S. E., Bochaca, F. R., Allende, D. G., & Fernandez, R. (2013). Green Areas and Microscale Thermal Comfort in Arid Environments: A Case Study in Mendoza, Argentina. Atmospheric and Climate Sciences, 03(03), 372–384. doi:10.4236/acs.2013.33039

Ren, C., Ng, E., & Katzschner, L. (2010). Urban climatic map studies: a review. International Journal of Climatology. doi:10.1002/joc.2237

Rosheidat, A., Hoffman, D., & Bryan, H. (2008). Visualizing Pedestrian Comfort Using Envi-met. In Third National Conference of IBPSA-USA.

Roth, M. (2007). Review of urban climate research in (sub) tropical regions. International Journal of Climatology, 1873(August), 1859–1873. Doi: 10.1002/joc

Roth, M. (2011). Review of urban climate research in (sub) tropical regions. In Urban Climatology on Tropical and Sub-Tropical Regions

Samarasinghe, G. B. (2009). Long-range Forecast of Climate Change : Sri Lanka Future Scenario Line-up. Retrieved from http://www.ips.lk/events/workshops/19_8_09_climate_change

Santo, M., Maggiotto, G., Stocker, J., Carruthers, D., & Di, S. (2012). 599 : Comparison of ADMS-Temperature and Humidity model and ENVI-met with measured temperature values, 8–11.

Scherer, D., & Endlicher, W. (2014). Editorial: Urban climate and heat stress – Part 1. Journal of the Geographical Society of Berlin, 144(3), 175–180. Doi: 10.12854/erde-144-13

Shi, Y., Ren, C, & Ng, E. (2012). 121 : Analysing the Wind and Thermal Environment of Beijing Downtown Commercial Street, ICUC8 – 8th International Conference on Urban Climates. Dublin, Ireland

Siu, L. W., & Hart, M. (2013). Quantifying urban heat island intensity in Hong Kong SAR, China. Environmental Monitoring and Assessment, 185(5), 4383–98. Doi: 10.1007/s10661-012-2876-6

Spangenberg, J, Shinzato, P, Johansson, E & Duarte, D (2008), Simulation of the influence of vegetation on microclimate and thermal comfort in the city of São Paulo, Revista SBAU, vol. 3, no. 2, pp. 1-19.

Srivanit, M. & Hokao, K. (2013). Evaluating the cooling effects of greening for improving the outdoor thermal environment at an institutional campus in the summer. Building and Environment, 66, pp.158–172.

Srivanit, M., & Kazunori, H. (2011a). Estimating Spatial Disaggregation of Urban Thermal Responsiveness on Summer Diurnal Range with a Numerical Modelling Approach. World Academy of Science, 11 No.5, 34–46. Doi: 112805-7676 IJCEE-IJENS

Srivanit, M., & Kazunori, H. (2011b). The Influence of Urban Morphology Indicators on Summer Diurnal Range of Urban Climate in Bangkok Metropolitan Area, Thailand. International Journal of Civil & Environmental Engineering IJCEE-IJENS, 11.

Stewart, I. D., (2011): Redefining the urban heat island. (Ph.D. Dissertation), Department of Geography, University of British Columbia, 352 pp. Retrieved from https://circle.ubc.ca/handle/2429/38069

Stewart, I., & Oke, T. (2009). Classifying Urban Climate Field Sites by "Local Climate Zones": The Case of Nagano, Japan. In The Seventh International Conference on Urban Climate. Yokohama, Japan.

Stewart, I. D., & Oke, T. R. (2012). "Local Climate Zones" for Urban Temperature Studies. Bulletin of the American Meteorological Society, 120525055949004. doi:10.1175/BAMS-D-11-00019.1

Szpirglas, J., & Voogt, J. A. (2003). A Validation and Performance Assessment of the Surface Heat Island Model. In Fifth International Conference on Urban Climate (ICUC-5). Lödz. Poland

Oke T. R., (1976) The distinction between canopy and boundary- layer urban heat islands, Atmosphere, vol. 14, no. 4, pp. 269– 727

Tan, C. L., Wong, N. H., & Jusuf, S. K. (2013). Outdoor Mean Radiant Temperature Estimation in the Tropical Urban Environment. Building and Environment, 64, 118–129. doi:10.1016/j.buildenv.2013.03.012

Tan, J, Zheng, Y, Tang, X, Guo, C, Li, L, Song ,G, Zhen, X, Yuan, D, Kalkstein AJ, Li, F, Chen, H. (2010). The urban heat island and its impact on heat waves and human health in Shanghai. Int J Biometeorol. 54, pp. 75–84

Taylor, B., & Guthrie, P. (2008). The first line of defence : Passive design at an urban scale. In Air Conditioning and the Low Carbon Cooling Challenge Network for Comfort and Energy Use in Buildings.

Thomas, G., Sherin, a. P., Ansar, S., & Zachariah, E. J. (2014). Analysis of Urban Heat Island in Kochi, India, Using a Modified Local Climate Zone Classification. Procedia Environmental Sciences, 21, 3–13. doi:10.1016/j.proenv.2014.09.002

Todhunter, P. E (1990) Microclimatic variations attributable to urban-canyon asymmetry and orientation. Physical Geography 11.131-141UDA.

Tomita T, Kusaka H, Akiyoshi R, Imasato Y (2006) Thermal and geometric controls on the rate of near-surface air temperature changes in a medium-size, mid-latitude city. In: Lindquist S, Grimmond CSB, Eliasson I (Eds.) Proc 6th Int Conf Urban Climate. (ICUC-6) University of Göteborg, p 338–341

Unger, J., Lelovics, E., & Gál, T. (2014). Local Climate Zone mapping using GIS methods in Szeged. Hungarian Geographical Bulletin, 63(1), 29–41. doi:10.15201/hungeobull.63.1.3

Unger, J., Savić, S., Gál, T., & Savi, S. (2011). Modelling of the Annual Mean Urban Heat Island Pattern for Planning of Representative Urban Climate Station Network. Advances in Meteorology, 2011, 1–9. doi:10.1155/2011/398613

Wachs, M (1979) Transportation for the Elderly: Changing Lifestyles, Changing Needs Martin. University of California Press, Berkeley, California

Wu, X. (2009). Summertime Urban Heat Island Effect in High – rise High – density Residential Development in the Inner City of Guangzhou, China. (Masters Thesis) The University of Hong Kong.

WUDAPT, (2014a). Mapping and the Citizen Sensor. Overview, pp.1–2. Available at: http://www.citizensensor-cost.eu/meetings/other-meetings/wudapt-dublin-7-9-jul-2014/.

WUDAPT, (2014b). The WUDAPT Project and Initial Workshop. Available at: http://geraldmills7.wix.com/wudapt

Yamamoto, Y. (2006). Measures to Mitigate Urban Heat Islands. Science & Technology Trends Quarterly Review, (54), 65–83.

Yang L, Li Y. (2009). City ventilation of Hong Kong at no-wind conditions. Atmospheric Environment. 43, pp. 3111–3121

Yang, F., Lau, S. S. Y. Y., & Qian, F. (2010). Summertime Heat Island Intensities in Three High-Rise Housing Quarters in Inner-City Shanghai China: Building Layout, Density and Greenery. Building and Environment, 45(1), 115–134. doi:10.1016/j.buildenv.2009.05.010

Yang, F., Lau, S. S. Y., Qian, F., & Taylor, P. (2011). Thermal comfort effects of urban design strategies in high-rise urban environments in a sub-tropical climate. Architectural Science Review, 54(4), 285–304. doi:10.1080/00038628.2011.613646

Zhao, C., Fu, G., Liu, X., & Fu, F. (2011). Urban Planning Indicators, Morphology and Climate Indicators : A Case Study for a North-South Transect of Beijing, China. Building and Environment, 46(5), 1174–1183. doi:10.1016/ j.buildenv.2010.12.009

Appendices

Appendix A

Form "C" - City of Colombo Development Plan - 1999 - (Source - UDA)

1 Class of Building	2 Extent (Square Metres)	3 Max. Number of Floors	4 Max. Height (Metres)	5 Min. Width of Site (Road frontage) (Metres)	6 Min. Road width (Metres)	7 Rear Space (Metres)	8 Space on other Sides (Metres)	9 Space in Front (Metres)	10 Plot Coverage #		11 Floor Are Ratio		12 Other Requirements
									Res.	Non Res.	Res.	Non Res.	
Low Rise													
-A	150-249	2(G+1)	7.50	6	03	2.3	-	01*	65%	80%	1:1.50	1:1.50	Nil
-B	150-249	3(G+2)	11.25	6	06	3.0	-	01*	65%	80%	1:2.00	1:2.25	Nil
Intermediate Rise													Lift and stand by generator
-A	250-399	5(G+4)	18.75	8	06	3.5	-	01*	65%	80%	1:3.00	1:3.75	
-B	400-749	6(G+5)	22.50	10	09	4.5	-	01*	65%	80%	1:3.75	1:4.50	
-C	750-999	8(G+7)	30.00	15	09	5.0	-	02	65%	80%	1:5.00	1:6.00	
Middle rise	1000-1999	12(G+11)	45.00	30	12	6.5	6.5	03	65%	70%	1:7.50	1:8.00	
High Rise	2000 & above	13 & above	46.00 & above	40	12	10.0	10.0	03	50%	50%	To be issued with Preliminary Planning Clearance		

Note: The Urban built form, character of the street and the natural environment within the context of local areas may have a continuity & harmony with the built and natural environment when the Development Guide Plans (DGP's) are enforced until such time the Authority may decide and instruct on open spaces around the buildings, Architectural form and the character of the street and the building etc.

* where there are no building lines # Plot coverage for new buildings Max. - Maximum
Min. - Minimum Res. - Resident

Appendix A

Form "C1" and "C2" - City of Colombo Development Plan (Amendment) - 2008

(Source - UDA)

Specifications for Development

Form C 1

Row No	Minimum Land Extent (sq.m.)	Minimum width between building lines of a public Street/Road (meters)	Minimum width of private Street/Road (meters)	Maximum permissible FAR
1	150 less than 250	-	3.0	1:1.5
2	150 less than 250	-	4.5	1:1.75
3	150 less than 250	-	6.0	1:2.0
4	150 less than 250	-	9.0	1:2.5
5	150 less than 250	12.2	12.2	1:3.0
6	250 less than 400	12.2	6.0	1:3.5
7	400 less than 500	12.2	9.0	1:4.5
8	500 less than 700	12.2	9.0	1:5.0
9	500 less than 700	15.0	12.2	1:5.5
10	700 less than 900	15.0	12.2	1:6.0
11	900 less than 1000	15.0	12.2	1:7.0
12	900 less than 1000	22	12.2	1:7.5
13	1000 less than 1500	22	12.2	1:8.0
14	1500 less than 2000	22	12.2	1;9.0
15	1500 less than 2000	24	12.2	1:9.5
16	2000 less than 2500	24	12.2	1:10.0
17	2500 less than 3000	24	12.2	1:12.0
18	3000 and above	24	12.2	Unlimited

Form - C 2

Building category	Maximum number of floors including ground floor	Minimum site frontage (m)	Maximum Plot coverage (%)	Open space around the building		
				Minimum Rear space (m)	Minimum one side space (m)	Minimum space on each side (m)
Low Rise	Ground floor	6.0	65	2.3	-	-
	2	6.0	65	2.3	-	-
	3	6.0	65	3.0	-	-
	4	6.0	65	3.0	-	-
Inter-mediate Rise	5	8.0	65	3.0	2.0	-
	6	10.0	65	4.0	2.0	-
	7	14.0	65	4.0	3.0	-
	8	16.0	65	4.0	3.0	-
Middle Rise	9	22.0	65	5.0	-	2.0
	10	26.0	65	5.0	-	3.0
	11	30.0	65	5.0	-	3.0
	12	30.0	65	5.0	-	3.0
High Rise	13	35.0	50	6.0	-	4.0
	14	35.0	50	6.0	-	4.0
	15-20	40.0	50	6.0	-	6.0
	21 & above	40.0	50	6.0	-	6.0

Appendix B - Local Climate Zone - Data Sheets. Source - Stewart, 2011

LOCAL CLIMATE ZONE CLASSIFICATION SYSTEM

Stewart ID. 2011. *Redefining the urban heat island*. Unpublished doctoral dissertation. University of British Columbia, Vancouver, Canada. https://circle.ubc.ca/handle/2429/38069

KEY TO DATASHEETS

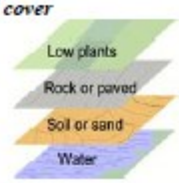
LCZ KEY	ZONE NAME	#

ZONE DEFINITION

Form: Description of building morphology, land cover, construction materials, tree geometry, and human activity. ***Function***: Land uses most likely associated with this zone. ***Location***: Expected location of the zone (core, periphery; city, countryside). ***Correspondence***: Comparable zones in the urban classification systems of Oke (2004) and Ellefsen (1990/91).

ZONE ILLUSTRATION

Land cover



High-angle photographs (© Can Stock Photo Inc.)

Objects

Low-level photographs (© Can Stock Photo Inc.)

ZONE PROPERTIES

Sky view factor ψ_{sky}
0 – 1
Fraction of sky hemisphere visible from ground level. Varies with height and spacing of buildings and trees. Affects surface radiational heating/cooling.

Aspect ratio H/W
0 – 3⁺
Mean height-to-width ratio of street canyons (LCZ 1–7), building spacing (LCZ 8–10), and tree spacing (LCZ A–F). Affects surface airflow and radiational heating/cooling.

Mean building/tree height z_H
0 – 50⁺ m
Geometric average of building heights (LCZ 1–10) and tree/plant heights (LCZ A–F). Affects surface reflectivity, flow regimes, and heat dispersion above ground.

Terrain roughness class
1 – 8
Davenport et al. (2000) classification of effective terrain roughness (z_0) for city and country landscapes: *1*–"sea" ($z_0 \sim 0.0002$ m); *2*–"smooth" ($z_0 \sim 0.005$ m); *3*–"open" ($z_0 \sim 0.03$ m); *4*–"roughly open" ($z_0 \sim 0.10$ m); *5*–"rough" ($z_0 \sim 0.25$ m); *6*–"very rough" ($z_0 \sim 0.5$ m); *7*–"skimming" ($z_0 \sim 1.0$ m); *8*–"chaotic" ($z_0 \sim 2$ m). Affects surface reflectivity, flow regimes, and heat dispersion above ground.

Building surface fraction λ_b
0 – 100 %
Proportion of ground surface with building cover. Affects surface reflectivity, flow regimes, and heat dispersion above ground.

Impervious surface fraction λ_i
0 – 100 %
Proportion of ground surface with impervious cover (paved, rock). Affects surface reflectivity, moisture availability, and heating/cooling potential.

Pervious surface fraction λ_v
0 – 100 %
Proportion of ground surface with pervious cover (bare soil, vegetation, water). Affects surface reflectivity, moisture availability, and heating/cooling potential.

Surface admittance μ
0 – 3,000⁺ $J\,m^{-2}\,s^{-1/2}\,K^{-1}$
Ability of surface to accept or release heat. Affects surface heat storage and heating/cooling rates. Values give typical range for surfaces in each LCZ (e.g., buildings, roads, soils, water). Varies with soil wetness and material density.

Albedo α
0 – 0.5
Surface reflectivity at local scale, under a clear midday sky. Affects surface radiational heating potential. Varies with surface wetness.

Anthropogenic heat flux Q_F
0 – 400⁺ $W\,m^{-2}$
Mean annual anthropogenic heat flux density at local scale. Heat sources include vehicle engines, industrial/domestic combustion processes, space cooling/heating, and human metabolism. Varies significantly with latitude, season, and population density.

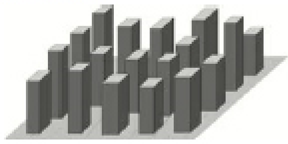
LCZ COMPACT HIGHRISE 1

DEFINITION

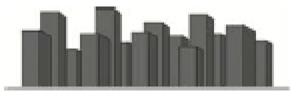
Form: Dense mix of tall buildings to tens of stories. Buildings free-standing, closely spaced. Sky view from street level significantly reduced. Buildings of steel, concrete, and glass construction. Land cover mostly paved; few or no trees. High space heating/cooling demand. Heavy traffic flow. *Function:* Commercial (office buildings, hotels); residential (apartment towers). *Location:* Core (downtown, central business district); periphery (highrise subcentre, highrise sprawl). *Correspondence:* UCZ1 (Oke 2004); Dc1 and Dc8 (Ellefsen 1990/91).

ILLUSTRATION

High angle



Low level



PROPERTIES

Sky view factor
0.2 – 0.4

Canyon aspect ratio
> 2

Mean building height
> 25 m

Terrain roughness class
8

Building surface fraction
40 – 60 %

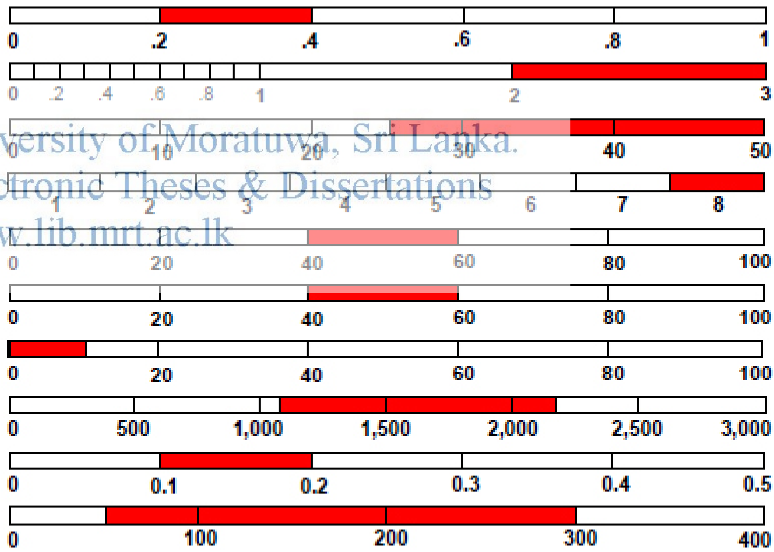
Impervious surface fraction
40 – 60 %

Pervious surface fraction
< 10 %

Surface admittance
1,100 – 2,200 J m^{-2} s$^{1/2}$ K^{-1}

Surface albedo
0.10 – 0.20

Anthropogenic heat flux
50 – 300 W m^{-2}



LCZ COMPACT MIDRISE 2

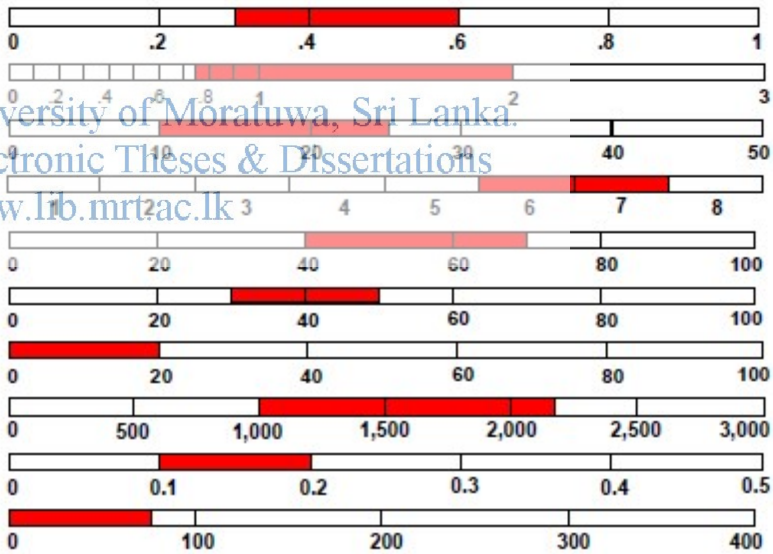
DEFINITION

Form: Attached or closely spaced buildings 3–9 stories tall. Buildings separated by narrow streets and inner courtyards. Buildings uniform in height. Sky view from street level significantly reduced. Heavy building materials (stone, concrete, brick, tile) and thick roofs and walls. Land cover mostly paved; few or no trees. Moderate space heating/cooling demand. Moderate to heavy traffic flow. *Function*: Residential (multi-unit housing; multistorey tenements); commercial (office buildings, hotels, retail shops); industrial (warehouses, factories). *Location*: Core (old city, old town; inner city, central business district); periphery (high-density sprawl). *Correspondence*: UCZ2 (Oke, 2004); A1, A2, A4, Dc2 (Ellefsen, 1990/91).

ILLUSTRATION

PROPERTIES

Sky view factor	0.3 – 0.6
Canyon aspect ratio	0.75 – 2
Mean building height	10 – 25 m
Terrain roughness class	6 – 7
Building surface fraction	40 – 70 %
Impervious surface fraction	30 – 50 %
Pervious surface fraction	< 20 %
Surface admittance	1,000 – 2,200 J m^{-2} $s^{1/2}$ K^{-1}
Surface albedo	0.10 – 0.20
Anthropogenic heat flux	< 75 W m^{-2}



LCZ — COMPACT LOWRISE — 3

DEFINITION

Form: Attached or closely spaced buildings 1–3 stories tall. Buildings small and tightly packed along narrow streets, often without discernable alignment. Sky view from street level significantly reduced. Heavy building materials (stone, concrete, brick, tile) and thick roofs and walls. Land cover mostly paved; few or no trees. Moderate space heating/cooling demand. Low-moderate traffic flow. *Function*: Residential (single-unit housing, high-density terrace/row housing); commercial (small retail shops). *Location*: Old or densely populated cities, towns, villages. Core (central or inner city); periphery (high-density sprawl). *Correspondence*: UCZ3 (Oke, 2004); Dc3 (Ellefsen, 1990/91).

ILLUSTRATION

High angle

Low level

PROPERTIES

Sky view factor
0.2 – 0.6

Canyon aspect ratio
0.75 – 1.5

Mean building height
3 – 10 m

Terrain roughness class
6

Building surface fraction
40 – 70 %

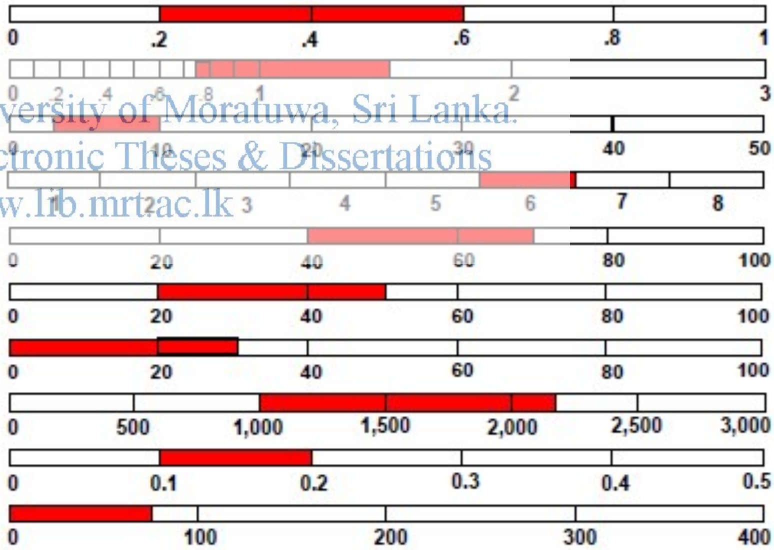
Impervious surface fraction
20 – 50 %

Pervious surface fraction
< 30 %

Surface admittance
1,000 – 2,200 J m^{-2} s$^{1/2}$ K^{-1}

Surface albedo
0.10 – 0.20

Anthropogenic heat flux
< 75 W m^{-2}



LCZ	OPEN HIGHRISE	4

DEFINITION

Form: Buildings tens of stories tall, set in open, geometric arrangement. Buildings uniform in height, width, and spacing. Sky view from ground level significantly reduced. Heavy building materials (concrete, steel, stone, glass) and thick roofs and walls. Roofs typically flat. Scattered trees and abundant plant cover. Moderate-low space heating/cooling demand. Moderate traffic flow. *Function*: Residential (apartment blocks, highrise housing estates, multistorey tenements). *Location*: Periphery. Densely populated cities. Socialist-style cities. *Correspondence*: Do2 (Ellefsen, 1990/91).

ILLUSTRATION

High angle

Low level

PROPERTIES

Sky view factor
0.5 – 0.7

Canyon aspect ratio
0.75 – 1.25

Mean building height
> 25 m

Terrain roughness class
7 – 8

Building surface fraction
20 – 40 %

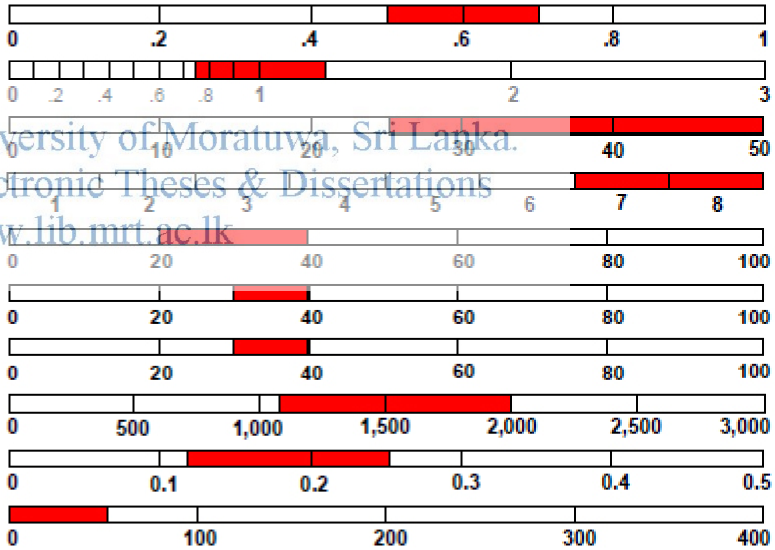
Impervious surface fraction
30 – 40 %

Pervious surface fraction
30 – 40 %

Surface admittance
1,100 – 2,000 J m^{-2} s$^{1/2}$ K^{-1}

Surface albedo
0.12 – 0.25

Anthropogenic heat flux
< 50 W m^{-2}



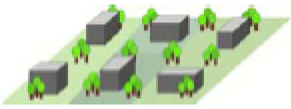
LCZ	OPEN MIDRISE	5

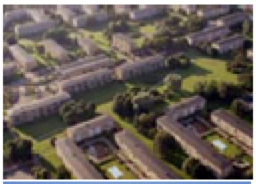
DEFINITION

Form: Open arrangement of buildings 3–9 stories tall. Sky view from street level slightly reduced. Heavy building materials (concrete, steel, stone, glass) and thick roofs and walls. Scattered trees and abundant plant cover. Low space heating/cooling demand. Low traffic flow. *Function*: Residential (multi-unit housing, multistorey tenements, apartment blocks); institutional (research/business parks, campuses); commercial (office buildings, hotels). *Location*: Periphery. *Correspondence*: UCZ6 (Oke, 2004); Do6 (Ellefsen, 1990/91).

ILLUSTRATION

High angle





Low level

PROPERTIES

Sky view factor
0.5 – 0.8

Canyon aspect ratio
0.3 – 0.75

Mean building height
10 – 25 m

Terrain roughness class
5 – 6

Building surface fraction
20 – 40 %

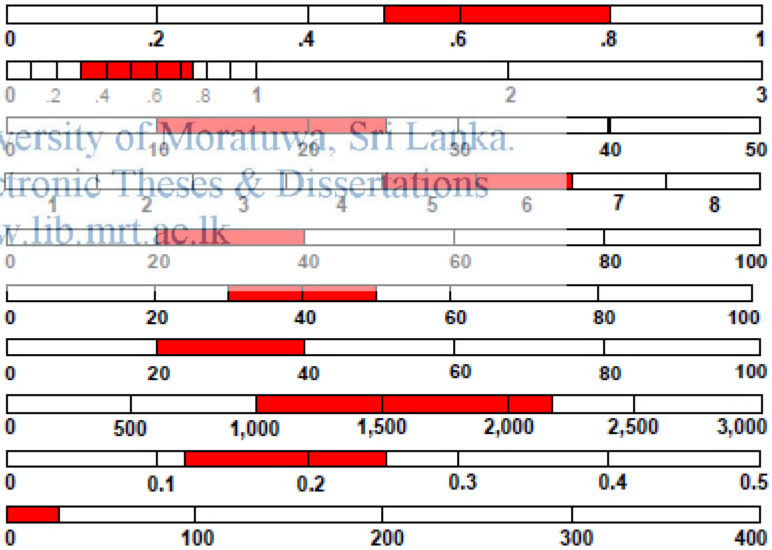
Impervious surface fraction
30 – 50 %

Pervious surface fraction
20 – 40 %

Surface admittance
1,000 – 2,200 J m^{-2} s$^{1/2}$ K^{-1}

Surface albedo
0.12 – 0.25

Anthropogenic heat flux
< 25 W m^{-2}



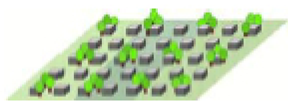
LCZ OPEN LOWRISE 6

DEFINITION

Form: Small buildings 1–3 stories tall; detached or attached in rows, often in grid pattern. Sky view from street level slightly reduced. Building materials vary (wood, brick, stone, tile). Scattered trees and abundant plant cover. Low space heating/cooling demand. Low traffic flow. *Function*: Residential (single or multi-unit housing, low density terrace/row housing); commercial (small retail shops). *Location*: City (medium density); periphery (suburbs). Commuter towns. Rural towns. *Correspondence*: UCZ5 (Oke 2004); Do3 (Ellefsen 1990/91).

ILLUSTRATION

High angle



Low level

PROPERTIES

Sky view factor
0.6 – 0.9

Canyon aspect ratio
0.3 – 0.75

Mean building height
3 – 10 m

Terrain roughness class
5 – 6

Building surface fraction
20 – 40 %

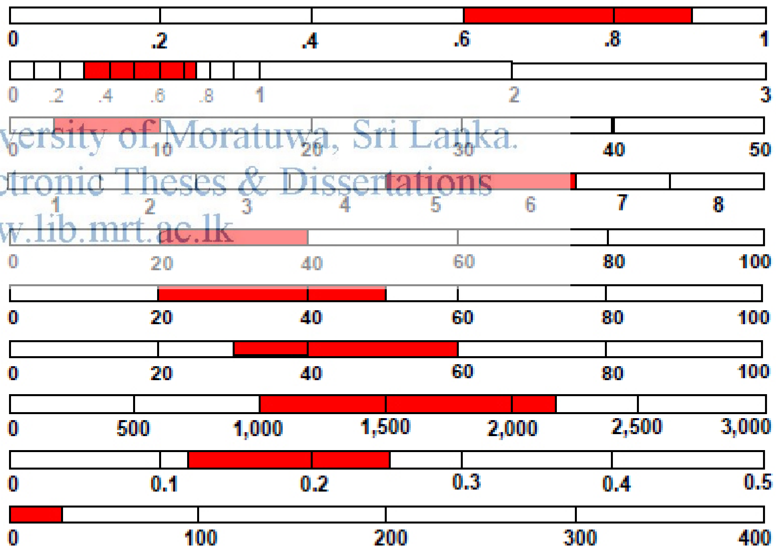
Impervious surface fraction
20 – 50 %

Pervious surface fraction
30 – 60 %

Surface admittance
1,000 – 2,200 J m^{-2} s$^{1/2}$ K^{-1}

Surface albedo
0.12 – 0.25

Anthropogenic heat flux
< 25 W m^{-2}



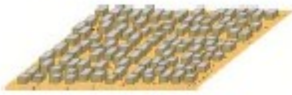
LCZ LIGHTWEIGHT LOWRISE 7

DEFINITION

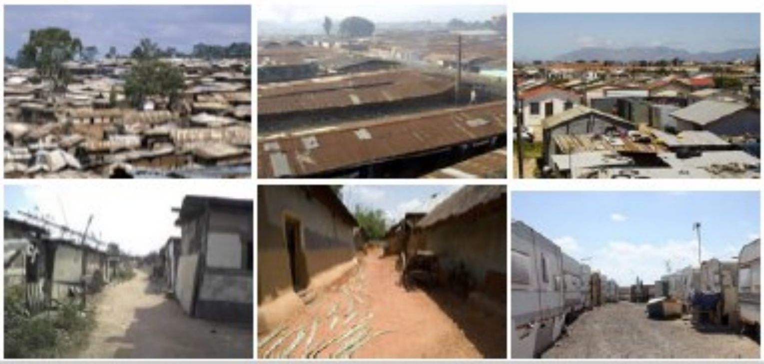
Form: Single-story buildings set in compact (often formless) arrangement, attached or closely spaced. Buildings separated by narrow roads and alleys. Little or no consolidated infrastructure. Sky view from ground level significantly reduced. Lightweight building materials (thatch, wood, bamboo, corrugated metal); thin walls and flat roofs. Few or no trees. Land cover hard packed (bare soil, sand). Population density high. Space heating/cooling demand nil. Low traffic flow. *Function*: Residential (informal settlements, low-cost housing, shantytowns, squatter settlements, mobile housing); agricultural (small-holder lots). *Location*: Periphery of large, developing cities. Extended metropolitan regions. Inner city. Rural towns.

ILLUSTRATION

High angle

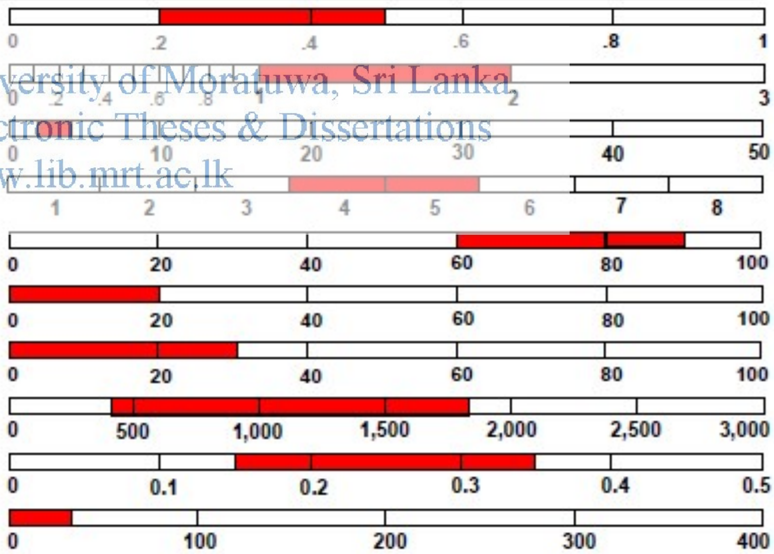


Low level



PROPERTIES

Sky view factor	0.2 – 0.5
Canyon aspect ratio	1 – 2
Mean building height	2 – 4 m
Terrain roughness class	4 – 5
Building surface fraction	60 – 90 %
Impervious surface fraction	< 20 %
Pervious surface fraction	< 30 %
Surface admittance	400 – 1,800 J m^{-2} $s^{1/2}$ K^{-1}
Surface albedo	0.15 – 0.35
Anthropogenic heat flux	< 35 W m^{-2}



LCZ LARGE LOWRISE 8

DEFINITION

Form: Large, low buildings 1–3 stories tall, separated by extensive paved surfaces. Buildings extend outward not upward; roofs flat. Sky view from ground level slightly reduced. Building materials vary (steel, concrete, metal). Few or no trees; land cover mostly paved. Moderate-low space heating/cooling demand. Moderate-heavy traffic flow. *Function*: Light industrial (modern warehousing); commercial (shopping centres, storage facilities); transportation hub (air, rail, truck, ship). *Location*: Periphery. *Correspondence*: UCZ4 (Oke, 2004); Do1, Do4 (Ellefsen, 1990/91).

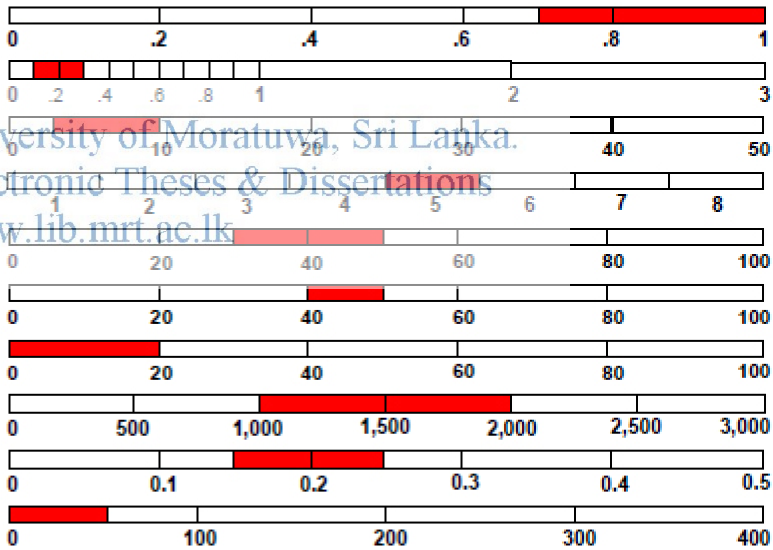
ILLUSTRATION

High angle

Low level

PROPERTIES

Sky view factor	> 0.7
Building aspect ratio	0.1 – 0.3
Mean building height	3 – 10 m
Terrain roughness class	5
Building surface fraction	30 – 50 %
Impervious surface fraction	40 – 50 %
Pervious surface fraction	< 20 %
Surface admittance	1,000 – 2,000 J m^{-2} s$^{1/2}$ K^{-1}
Surface albedo	0.15 – 0.25
Anthropogenic heat flux	< 50 W m^{-2}



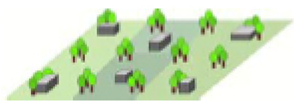
LCZ SPARSELY BUILT 9

DEFINITION

Form: Small or medium-sized buildings widely spaced across natural landscape. Full sky view from ground level. Building materials vary. Scattered trees and abundant plant cover. Space heating/cooling demand negligible. Low traffic flow. *Function*: Residential (single or multi-unit housing); commercial (retail shops, office buildings); institutional (research/business parks, campuses); agricultural (farms, country estates). *Location*: Periphery (low-density suburbs). Extended metropolitan regions. Newly developed urban tracts. Rural towns. Lightly settled countryside. *Correspondence*: UCZ7 (Oke, 2004).

ILLUSTRATION

High angle



Low level

PROPERTIES

Sky view factor
> 0.8

Building aspect ratio
0.1 – 0.25

Mean building height
3 – 10 m

Terrain roughness class
5 – 6

Building surface fraction
10 – 20 %

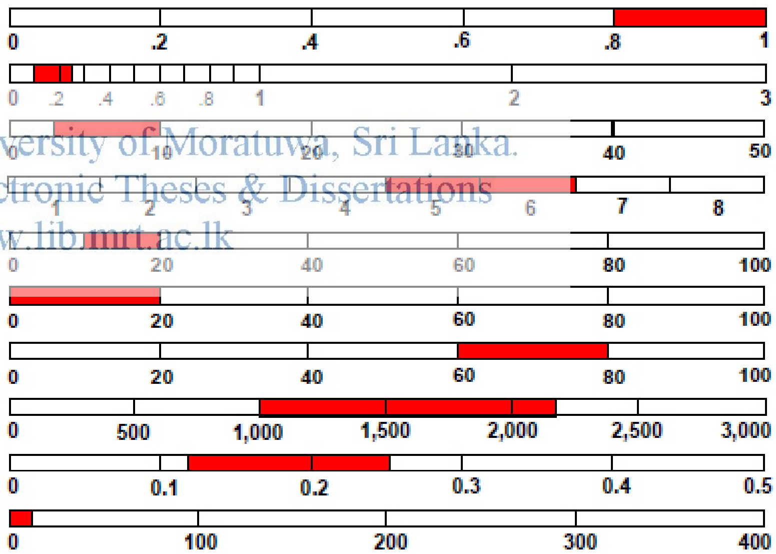
Impervious surface fraction
< 20 %

Pervious surface fraction
60 – 80 %

Surface admittance
1,000 – 2,200 J m^{-2} $s^{1/2}$ K^{-1}

Surface albedo
0.12 – 0.25

Anthropogenic heat flux
< 10 W m^{-2}



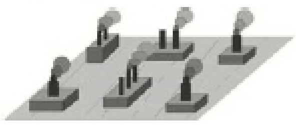
LCZ	HEAVY INDUSTRY	10

DEFINITION

Form: Highly irregular mix of low and midrise industrial structures (tanks, towers, stacks). Structures openly spaced on hard-packed surfaces. Sky view from ground level slightly reduced. Building materials vary (steel, concrete, metal). Few or no trees. High demand for space heating/cooling. Large quantities of waste heat and atmospheric pollutants released from mechanical and chemical processing (smelting, pulping, distilling). Low traffic flow. *Function:* Industrial (factories, refineries, mills, plants). *Location:* City or country.

ILLUSTRATION

High angle



Low level

PROPERTIES

Sky view factor
0.6 – 0.9

Building aspect ratio
0.2 – 0.5

Mean building height
5 – 15 m

Terrain roughness class
5 – 6

Building surface fraction
20 – 30 %

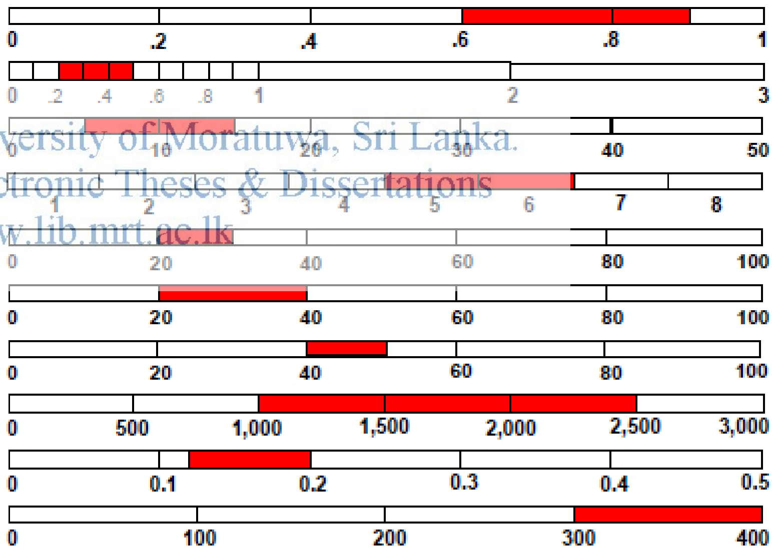
Impervious surface fraction
20 – 40 %

Pervious surface fraction
40 – 50 %

Surface admittance
1,000 – 2,500 J m^{-2} s$^{1/2}$ K^{-1}

Surface albedo
0.12 – 0.20

Anthropogenic heat flux
> 300 W m^{-2}



LCZ | DENSE TREES | A

DEFINITION

Form: Heavily wooded landscape of deciduous and/or evergreen trees. Trees closely spaced across pervious ground (low plants). Sky view from ground level significantly reduced. Few or no roads or buildings. Space heating/cooling demand nil. Low or no traffic flow. *Function*: Natural forest (equatorial, tropical, midlatitude). Tree cultivation (dense orchards, plantations). Urban recreation (wooded parks, greenbelts). *Location*: City or country.

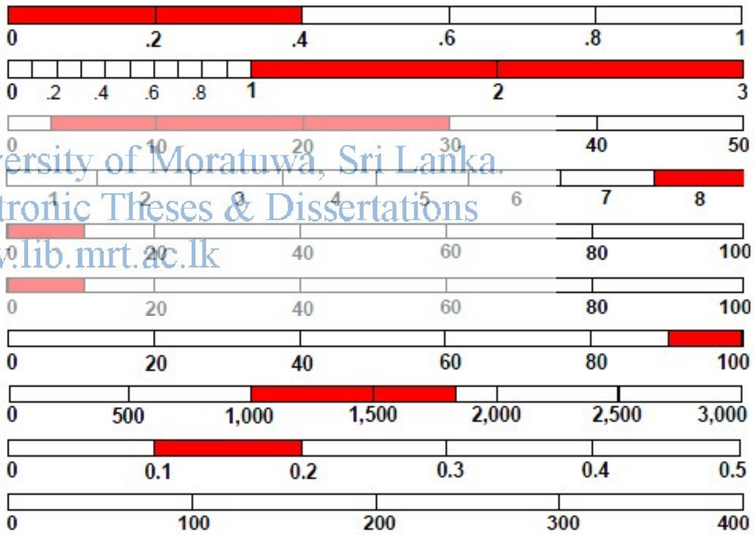
ILLUSTRATION

High angle

Low level

PROPERTIES

Sky view factor	< 0.4
Tree aspect ratio	> 1
Mean tree height	3 – 30⁺ m
Terrain roughness class	8
Building surface fraction	< 10 %
Impervious surface fraction	< 10 %
Pervious surface fraction	> 90 %
Surface admittance	1,000 – 1,800 J m^{-2} $s^{1/2}$ K^{-1}
Surface albedo	0.10 – 0.20
Anthropogenic heat flux	0 W m^{-2}



LCZ	SCATTERED TREES	B

DEFINITION

Form: Lightly wooded landscape of deciduous and/or evergreen trees. Trees scattered across pervious ground (low plants). Sky view from ground level slightly reduced. Few or no roads or buildings. Space heating/cooling demand nil. Low or no traffic flow. ***Function***: Natural forest (savannah, parkland, high latitude). Tree cultivation (orchards, groves, plantations). Urban recreation (parks, green spaces). ***Location***: City or country.

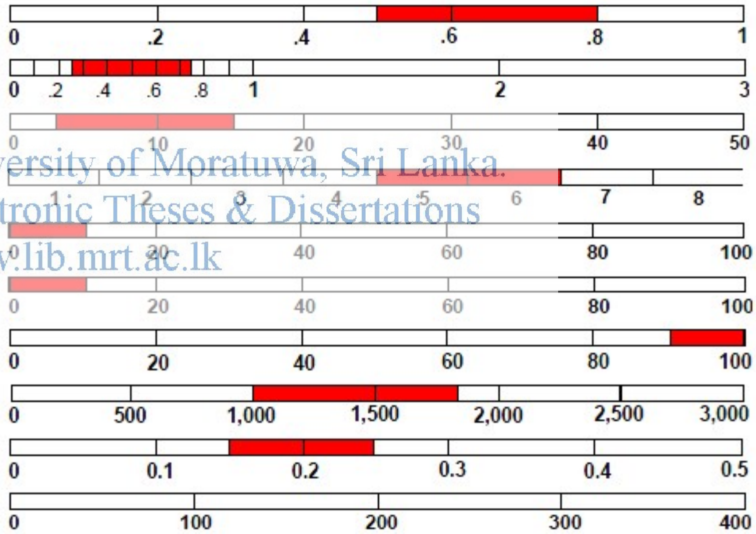
ILLUSTRATION

High angle

Low level

PROPERTIES

Sky view factor	0.5 – 0.8
Tree aspect ratio	0.25 – 0.75
Mean tree height	3 – 15 m
Terrain roughness class	5 – 6
Building surface fraction	< 10 %
Impervious surface fraction	< 10 %
Pervious surface fraction	> 90 %
Surface admittance	1,000 – 1,800 J m^{-2} s$^{1/2}$ K^{-1}
Surface albedo	0.15 – 0.25
Anthropogenic heat flux	0 W m^{-2}



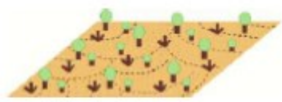
LCZ — BUSH, SCRUB — C

DEFINITION

Form: Open shrubs, bushes, and short, woody trees on pervious ground (bare soil or sand; sparse plant cover). Full sky view from ground level. Few or no roads or buildings. Space heating/cooling demand nil. Low or no traffic flow. ***Function***: Desert scrubland; interior scrubland; Mediterranean scrubland. Tree cultivation (orchards/plantations of dwarf or bush trees). Agriculture (unimproved pasture). ***Location***: City or country.

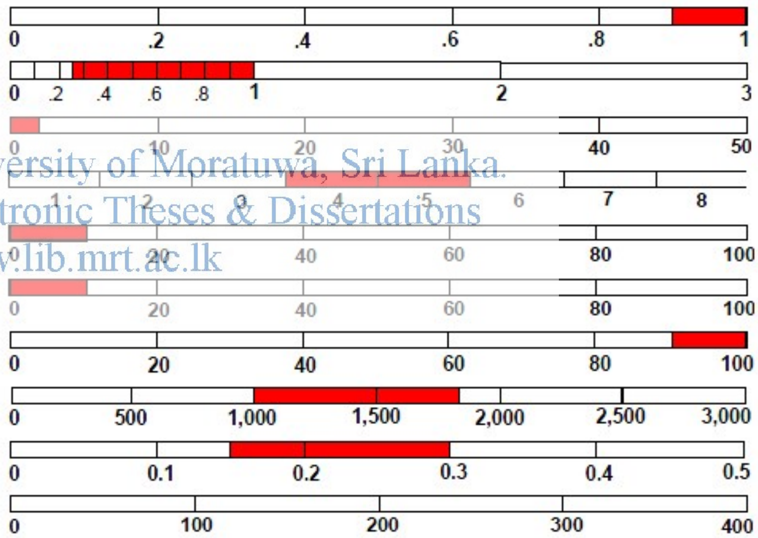
ILLUSTRATION

High angle



Low level

PROPERTIES



Sky view factor	> 0.9
Tree aspect ratio	0.25 – 1
Mean plant height	< 2 m
Terrain roughness class	4 – 5
Building surface fraction	< 10 %
Impervious surface fraction	< 10 %
Pervious surface fraction	> 90 %
Surface admittance	1,000 – 1,800 J m^{-2} s$^{1/2}$ K^{-1}
Surface albedo	0.15 – 0.30
Anthropogenic heat flux	0 W m^{-2}

LCZ	LOW PLANTS	D

DEFINITION

Form: Featureless landscape of pervious ground, predominantly low plant cover. Few or no trees, roads, or buildings. Full sky view from ground level. Space heating/cooling demand nil. Low or no traffic flow. ***Function***: Natural grassland (savannah, steppe). Agriculture (pasture, arable farmland). Urban recreation (grassy parks, green spaces). ***Location***: City or country. ***Correspondence***: UCZ7 (Oke 2004).

ILLUSTRATION

High angle

Low level

PROPERTIES

Sky view factor > 0.9

Tree aspect ratio < 0.1

Mean plant height < 1 m

Terrain roughness class 3 – 4

Building surface fraction < 10 %

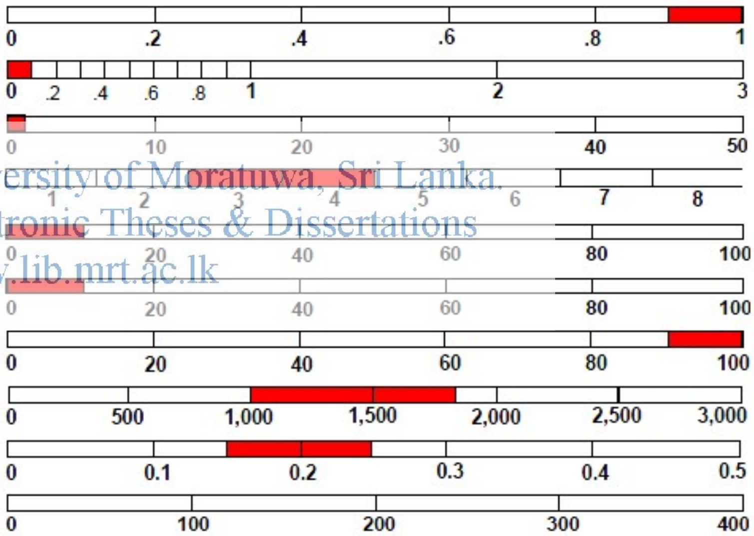
Impervious surface fraction < 10 %

Pervious surface fraction > 90 %

Surface admittance 1,000 – 1,800 J m^{-2} s$^{1/2}$ K^{-1}

Surface albedo 0.15 – 0.25

Anthropogenic heat flux 0 W m^{-2}



LCZ BARE ROCK OR PAVED E

DEFINITION

Form: Featureless landscape of impervious ground, predominantly rock, paved, or hard packed. Ground cover varies (gravel, laterite, exposed bedrock; asphalt, concrete). Few or no trees, plants, or buildings. Full sky view from ground level. Space heating/cooling demand nil. Low or no traffic flow. ***Function***: Natural desert (cold, rock); geological shield. Transportation (car parks, container ports, freight terminals, airport aprons). ***Location***: City or country.

ILLUSTRATION

High angle

Low level

PROPERTIES

Sky view factor
> 0.9

Tree aspect ratio
< 0.1

Mean plant height
< 0.25 m

Terrain roughness class
1 – 2

Building surface fraction
< 10 %

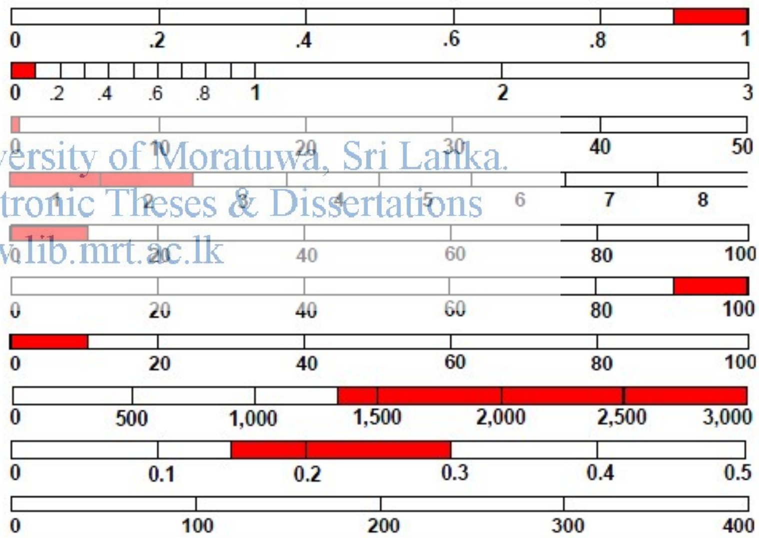
Impervious surface fraction
> 90 %

Pervious surface fraction
< 10 %

Surface admittance
1,300 – 3,000 J m^{-2} $s^{1/2}$ K^{-1}

Surface albedo
0.15 – 0.30

Anthropogenic heat flux
0 W m^{-2}



LCZ BARE SOIL OR SAND F

DEFINITION

Form: Featureless landscape of pervious ground, predominantly soil or sand. Few or no trees, plants, roads, or buildings. Full sky view from ground level. Space heating/cooling demand nil. Low or no traffic flow. ***Function***: Natural desert (hot). Agriculture (plowed or fallow fields). Barren land. ***Location***: City or country.

ILLUSTRATION

High angle

Low level

PROPERTIES

Sky view factor
> 0.9

Tree aspect ratio
< 0.1

Mean plant height
< 0.25 m

Terrain roughness class
1 – 2

Building surface fraction
< 10 %

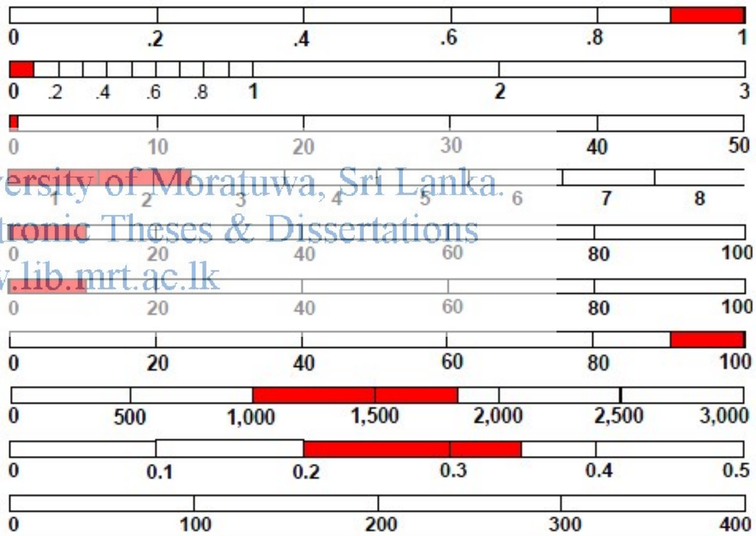
Impervious surface fraction
< 10 %

Pervious surface fraction
> 90 %

Surface admittance
1,000 – 1,800 J m^{-2} s$^{1/2}$ K^{-1}

Surface albedo
0.20 – 0.35

Anthropogenic heat flux
0 W m^{-2}



LCZ	WATER	G

DEFINITION

Form: Large, open water bodies such as seas, lakes, and bays, or smaller bodies like rivers, reservoirs, and lagoons. Few or no roughness features. Full sky view. *Function*: Natural water systems. Recreation. Transportation. Industry. *Location*: City (urban lakes, rivers, harbours) or country.

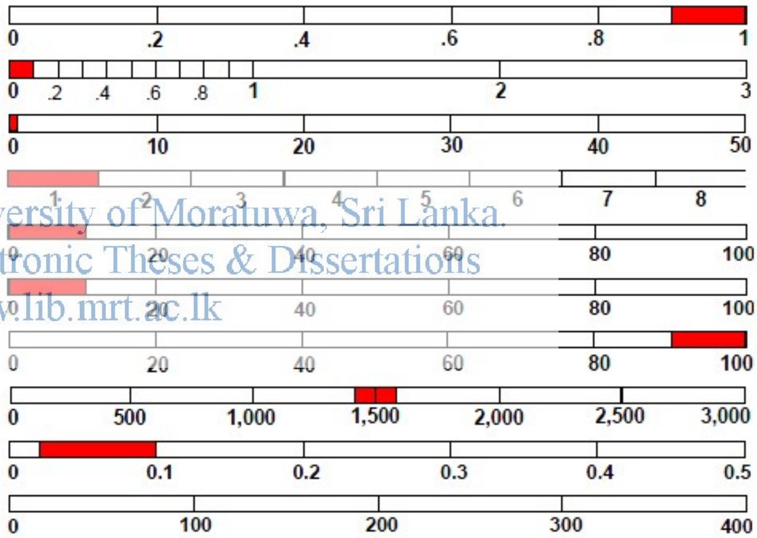
ILLUSTRATION

High angle

Low level

PROPERTIES

Sky view factor	> 0.9
Tree aspect ratio	< 0.1
Mean plant height	< 0.25 m
Terrain roughness class	1
Building surface fraction	< 10 %
Impervious surface fraction	< 10 %
Pervious surface fraction	> 90 %
Surface admittance	1,500 J m^{-2} $s^{1/2}$ K^{-1}
Surface albedo	0.02 – 0.10
Anthropogenic heat flux	0 W m^{-2}



Appendix C - Values of geometric and surface cover properties for local climate zones.
All properties are unitless except height of roughness elements (m). Source - Stewart & Oke, 2012

Local climate zone (LCZ)	Sky view factor[a]	Aspect ratio[b]	Building surface fraction[c]	Impervious surface fraction[d]	Pervious surface fraction[e]	Height of roughness elements[f]	Terrain roughness class[g]
LCZ 1 *Compact high-rise*	0.2–0.4	> 2	40–60	40–60	< 10	> 25	8
LCZ 2 *Compact midrise*	0.3–0.6	0.75–2	40–70	30–50	< 20	10–25	6–7
LCZ 3 *Compact low-rise*	0.2–0.6	0.75–1.5	40–70	20–50	< 30	3–10	6
LCZ 4 *Open high-rise*	0.5–0.7	0.75–1.25	20–40	30–40	30–40	>25	7–8
LCZ 5 *Open midrise*	0.5–0.8	0.3–0.75	20–40	30–50	20–40	10–25	5–6
LCZ 6 *Open low-rise*	0.6–0.9	0.3–0.75	20–40	20–50	30–60	3–10	5–6
LCZ 7 *Lightweight low-rise*	0.2–0.5	1–2	60–90	< 20	<30	2–4	4–5
LCZ 8 *Large low-rise*	>0.7	0.1–0.3	30–50	40–50	<20	3–10	5
LCZ 9 *Sparsely built*	> 0.8	0.1–0.25	10–20	< 20	60–80	3–10	5–6
LCZ 10 *Heavy industry*	0.6–0.9	0.2–0.5	20–30	20–40	40–50	5–15	5–6
LCZ A *Dense trees*	<0.4	>1	<10	<10	>90	3–30	8
LCZ B *Scattered trees*	0.5–0.8	0.25–0.75	<10	<10	>90	3–15	5–6
LCZ C *Bush, scrub*	0.7–0.9	0.25–1.0	<10	<10	>90	<2	4–5
LCZ D *Low plants*	>0.9	<0.1	<10	<10	>90	<1	3–4
LCZ E *Bare rock or paved*	>0.9	<0.1	<10	>90	<10	<0.25	1–2
LCZ F *Bare soil or sand*	>0.9	<0.1	<10	<10	>90	< 0.25	1–2
LCZ G *Water*	>0.9	<0.1	<10	<10	>90	–	1

[a] Ratio of the amount of sky hemisphere visible from ground level to that of an unobstructed hemisphere

[b] Mean height-to-width ratio of street canyons (LCZs 1–7), building spacing (LCZs 8–10), and tree spacing (LCZs A–G)

[c] Ratio of building plan area to total plan area (%)

[d] Ratio of impervious plan area (paved, rock) to total plan area (%)

[e] Ratio of pervious plan area (bare soil, vegetation, water) to total plan area (%)

[f] Geometric average of building heights (LCZs 1–10) and tree/plant heights (LCZs A–F) (m)

[g] Davenport et al.'s (2000) classification of effective terrain roughness (z_0) for city and country landscapes. See Table 5 for class descriptions

Appendix C - Values of thermal, radiative, and metabolic properties for local climate zones. All values are representative of the local scale. Source - Stewart & Oke, 2012

Local climate zone (LCZ)	Surface admittance[a]	Surface albedo[b]	Anthropogenic heat output[c]
LCZ 1 *Compact high-rise*	1,500–1,800	0.10–0.20	50–300
LCZ 2 *Compact midrise*	1,500–2,200	0.10–0.20	<75
LCZ 3 *Compact low-rise*	1,200–1,800	0.10–0.20	<75
LCZ 4 *Open high-rise*	1,400–1,800	0.12–0.25	<50
LCZ 5 *Open midrise*	1,400–2,000	0.12–0.25	<25
LCZ 6 *Open low-rise*	1,200–1,800	0.12–0.25	<25
LCZ 7 *Lightweight low-rise*	800–1,500	0.15–0.35	<35
LCZ 8 *Large low-rise*	1,200–1,800	0.15–0.25	<50
LCZ 9 *Sparsely built*	1,000–1,800	0.12–0.25	<10
LCZ 10 *Heavy industry*	1,000–2,500	0.12–0.20	>300
LCZ A *Dense trees*	unknown	0.10–0.20	0
LCZ B *Scattered trees*	1,000–1,800	0.15–0.25	0
LCZ C *Bush, scrub*	700–1,500	0.15–0.30	0
LCZ D *Low plants*	1,200–1,600	0.15–0.25	0
LCZ E *Bare rock or paved*	1,200–2,500	0.15–0.30	0
LCZ F *Bare soil or sand*	600–1,400	0.20–0.35	0
LCZ G *Water*	1,500	0.02–0.10	0

[a] Ability of surface to accept or release heat (J m^{-2} $s^{-1/2}$ K^{-1}). Varies with soil wetness and material density. Few estimates of local-scale admittance exist in the literature; values given here are therefore subjective and should be used cautiously. Note that the "surface" in LCZ A is undefined and its admittance unknown.

[b] Ratio of the amount of solar radiation reflected by a surface to the amount received by it. Varies with surface color, wetness, and roughness.

[c] Mean annual heat flux density (W m^{-2}) from fuel combustion and human activity (transportation, space cooling/heating, industrial processing, human metabolism). Varies significantly with latitude, season, and population density.

Appendix D - Weather Station Data for Urban and Rural site comparison

Colombo-Ratmalana regional data - Urban simulation.

EnergyPlus Weather Converter V7.2.0.006
Statistics for LKA_Colombo-Ratmalana.434670_SWERAEPW
Location -- COLOMBO/RATMALANA - LKA
{N 6° 49'} {E 79° 52'} {GMT +6.0 Hours}
Elevation -- 5m above sea level
Standard Pressure at Elevation -- 101265Pa
Data Source -- SWERA

WMO Station 434670

- Displaying Design Conditions calculated from this weather file.
- The following design temperature statistics are calculated based on THIS weather file ONLY
- and may not be representative of a long-term period of record normally used for
- design temperatures. Also, note that dew point temperatures are listed where
- wet-bulb temperatures are normally presented.
- Heating/Cooling Degree Days/Hours calculated from this weather file are later in this report.

- Monthly Statistics for Dry Bulb temperatures °C

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maximum	32.4	32.6	33.1	32.7	33.0	31.2	30.6	31.9	33.0	31.6	33.5	32.0
Day:Hour	23:15	9:15	20:12	19:12	23:06	3:15	4:15	11:15	14:12	4:12	22:15	29:12
Minimum	20.9	17.3	21.7	23.1	21.9	23.0	23.7	21.4	23.0	21.9	20.8	21.0
Day:Hour	2:06	11:06	3:06	9:06	15:04	16:09	15:06	13:06	28:06	16:06	22:06	23:06
Daily Avg	26.6	26.1	27.7	28.3	28.8	27.8	27.3	27.1	27.6	27.1	26.4	26.2

- Maximum Dry Bulb temperature of 33.5°C on Nov 22
- Minimum Dry Bulb temperature of 17.3°C on Feb 11

- Monthly Statistics for Dew Point temperatures °C

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maximum	28.0	26.2	28.2	27.1	27.3	27.4	25.1	26.1	26.0	26.0	26.0	25.6
Day:Hour	23:12	18:18	7:12	22:18	8:12	1:15	12:15	5:12	14:15	9:21	9:24	4:18
Minimum	18.0	14.3	18.2	21.7	21.9	20.0	22.1	-11.0	21.0	3.0	12.2	17.3
Day:Hour	3:18	7:12	3:12	7:18	15:04	15:03	2:23	23:12	14:12	19:09	28:12	23:12
Daily Avg	22.2	22.5	23.5	24.7	25.2	24.3	23.8	23.3	23.5	23.5	22.4	23.0

- Maximum Dew Point temperature of 28.2°C on Mar 7
- Minimum Dew Point temperature of -11.0°C on Aug 23

- Average Hourly Statistics for Dry Bulb temperatures °C

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01- 1:00	24.6	23.8	25.5	26.5	27.8	26.9	26.3	26.0	26.5	25.9	24.8	24.4
1:01- 2:00	24.3	23.6	25.1	26.3	27.5	26.8	26.2	25.9	26.5	25.8	24.4	24.2
2:01- 3:00	24.1	23.5	24.7	26.1	27.2	26.7	26.1	25.7	26.4	25.6	24.0	24.0
3:01- 4:00	23.9	23.1	24.4	25.9	26.9	26.7	26.0	25.5	26.3	25.5	23.7	23.8
4:01- 5:00	23.7	22.7	24.2	25.7	26.8	26.6	26.0	25.4	26.2	25.3	23.4	23.7
5:01- 6:00	23.5	22.4	23.9	25.5	26.7	26.6	25.9	25.4	26.1	25.2	23.3	23.5
6:01- 7:00	24.1	23.3	25.1	26.4	27.3	27.0	26.3	25.9	26.7	25.8	24.3	24.4
7:01- 8:00	24.8	24.3	26.3	27.4	27.9	27.3	26.8	26.4	27.3	26.4	25.4	25.3
8:01- 9:00	25.6	25.4	27.5	28.3	28.5	27.7	27.3	26.9	27.8	27.1	26.4	26.2
9:01-10:00	26.9	26.8	28.6	29.2	29.2	28.3	27.7	27.6	28.4	27.7	27.3	27.3
10:01-11:00	28.2	28.2	29.8	30.1	29.9	28.9	28.2	28.2	29.0	28.4	28.3	28.3
11:01-12:00	29.5	29.6	30.9	31.1	30.6	29.5	28.7	28.9	29.6	29.1	29.2	29.3
12:01-13:00	29.7	29.7	30.9	31.0	30.6	29.4	28.7	28.9	29.5	28.9	29.2	29.2
13:01-14:00	29.8	29.8	30.8	31.0	30.7	29.2	28.8	28.9	29.4	28.7	29.2	29.1
14:01-15:00	29.9	29.8	30.8	30.9	30.7	29.1	28.9	28.9	29.3	28.6	29.2	28.9
15:01-16:00	29.5	29.3	30.5	30.5	30.5	28.8	28.6	28.6	28.9	28.4	28.8	28.4
16:01-17:00	29.1	28.7	30.1	30.0	30.2	28.5	28.3	28.2	28.4	28.1	28.4	27.9
17:01-18:00	28.7	28.2	29.8	29.8	30.0	28.3	28.0	27.8	28.0	27.9	27.8	27.4
18:01-19:00	28.1	27.4	29.2	29.3	29.7	28.0	27.7	27.4	27.7	27.6	27.2	26.9
19:01-20:00	27.4	26.6	28.6	28.7	29.4	27.8	27.4	27.1	27.3	27.3	26.8	26.4
20:01-21:00	26.8	25.8	28.0	28.1	29.1	27.6	27.1	26.7	27.0	26.9	26.4	25.9
21:01-22:00	26.1	25.2	27.4	27.7	28.8	27.4	26.9	26.6	26.8	26.6	26.0	25.4
22:01-23:00	25.4	24.6	26.8	27.1	28.5	27.2	26.7	26.4	26.7	26.4	25.6	25.0
23:01-24:00	24.8	24.0	26.1	26.6	28.2	27.0	26.4	26.2	26.6	26.1	25.3	24.5
Max Hour	15	15	12	12	15	12	15	15	12	12	12	12
Min Hour	6	6	6	6	6	6	6	6	6	6	6	6

- Average Hourly Statistics for Dew Point temperatures °C

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01- 1:00	22.2	22.7	23.5	24.6	25.1	24.3	23.8	23.6	23.5	23.9	22.6	23.0
1:01- 2:00	22.2	22.5	23.3	24.6	25.0	24.2	23.8	23.6	23.4	23.7	22.5	23.0
2:01- 3:00	22.0	22.2	23.2	24.5	24.9	24.0	23.7	23.6	23.3	23.5	22.3	22.9
3:01- 4:00	22.0	22.1	23.1	24.5	24.8	24.1	23.7	23.6	23.3	23.3	22.2	22.8
4:01- 5:00	21.9	21.9	23.0	24.4	24.7	24.1	23.7	23.6	23.3	23.0	22.1	22.8
5:01- 6:00	21.8	21.8	22.9	24.4	24.7	24.1	23.6	23.6	23.3	22.8	22.1	22.8
6:01- 7:00	22.0	22.1	23.1	24.5	24.9	24.1	23.7	23.7	23.4	22.9	22.2	22.9
7:01- 8:00	22.2	22.4	23.3	24.6	25.2	24.2	23.8	23.8	23.5	23.1	22.3	22.9
8:01- 9:00	22.4	22.7	23.6	24.7	25.4	24.2	23.9	23.9	23.6	23.3	22.3	23.0
9:01-10:00	22.3	22.6	23.5	24.7	25.5	24.3	23.9	23.6	23.6	23.3	22.2	23.0
10:01-11:00	22.1	22.6	23.5	24.7	25.5	24.4	23.9	23.2	23.7	23.3	22.0	22.9
11:01-12:00	21.9	22.6	23.4	24.8	25.5	24.5	24.0	22.9	23.7	23.4	21.8	22.8
12:01-13:00	21.9	22.5	23.5	24.8	25.5	24.5	23.9	22.9	23.7	23.5	22.0	22.9
13:01-14:00	21.8	22.5	23.6	24.9	25.5	24.5	23.9	22.9	23.8	23.6	22.1	23.1
14:01-15:00	21.8	22.4	23.6	24.9	25.5	24.5	23.8	22.9	23.8	23.7	22.3	23.2
15:01-16:00	22.2	22.5	23.8	24.9	25.4	24.4	23.8	22.9	23.7	23.8	22.4	23.2
16:01-17:00	22.5	22.5	23.9	24.9	25.4	24.3	23.8	22.8	23.5	23.8	22.6	23.2
17:01-18:00	22.9	22.6	24.1	24.9	25.3	24.1	23.7	22.8	23.4	23.8	22.8	23.2
18:01-19:00	22.9	22.7	24.0	24.9	25.3	24.2	23.7	23.0	23.5	23.8	22.8	23.2
19:01-20:00	22.7	22.7	24.0	24.8	25.3	24.3	23.8	23.1	23.5	23.8	22.8	23.2
20:01-21:00	22.6	22.8	23.9	24.8	25.2	24.3	23.8	23.3	23.6	23.9	22.8	23.1
21:01-22:00	22.5	22.8	23.8	24.8	25.3	24.4	23.8	23.4	23.6	23.9	22.8	23.1
22:01-23:00	22.4	22.8	23.8	24.7	25.3	24.4	23.8	23.6	23.6	23.9	22.8	23.1
23:01-24:00	22.4	22.9	23.7	24.6	25.3	24.4	23.7	23.7	23.6	24.0	22.7	23.2
Max Hour	18	24	18	15	12	15	12	9	15	24	21	18
Min Hour	15	6	6	6	6	3	6	18	3	6	12	6

- Monthly Statistics for Relative Humidity %

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maximum	100	100	100	100	100	100	97	100	100	100	100	100
Day:Hour	8:06	2:01	1:06	4:06	4:24	10:06	9:06	9:06	27:21	1:12	5:19	3:24
Minimum	48	38	44	58	61	59	66	6	49	19	30	43
Day:Hour	5:15	7:12	3:12	9:12	23:06	18:12	26:15	23:12	14:12	19:09	28:12	23:15
Daily Avg	78	82	79	82	81	81	82	81	79	82	80	84

- Average Hourly Relative Humidity %

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01- 1:00	87	94	89	89	86	86	86	87	84	89	88	92
1:01- 2:00	88	94	90	91	86	86	86	88	84	89	89	93
2:01- 3:00	89	93	91	91	87	85	87	89	84	89	90	94
3:01- 4:00	90	94	92	92	88	86	87	89	84	88	91	94
4:01- 5:00	90	95	93	93	88	86	88	90	85	88	92	95
5:01- 6:00	91	97	94	94	89	87	88	90	85	89	93	96
6:01- 7:00	89	93	89	89	87	85	86	88	83	86	88	91
7:01- 8:00	86	90	84	85	85	83	84	86	80	84	84	87
8:01- 9:00	83	85	79	81	84	82	82	84	78	82	79	83
9:01-10:00	76	79	74	77	80	79	80	79	75	78	75	78
10:01-11:00	70	72	69	73	78	77	78	76	73	75	70	73
11:01-12:00	64	67	65	70	75	75	76	73	71	72	66	69
12:01-13:00	64	66	65	70	74	75	75	73	71	73	67	70
13:01-14:00	63	66	66	70	74	76	75	72	72	75	67	71
14:01-15:00	63	66	66	71	74	77	74	72	72	76	68	72
15:01-16:00	65	68	68	73	75	77	75	73	74	77	70	74
16:01-17:00	68	[illegible]	[illegible]	[illegible]	75	78	77	75	75	78	72	76
17:01-18:00	72	73	72	75	76	78	78	76	76	78	75	79
18:01-19:00	74	76	74	78	77	80	79	78	78	80	77	81
19:01-20:00	77	80	76	80	79	81	80	80	80	82	80	83
20:01-21:00	79	84	79	82	80	83	82	82	82	84	82	85
21:01-22:00	81	87	81	84	81	84	83	84	83	85	83	88
22:01-23:00	84	90	84	87	83	85	84	85	83	87	85	90
23:01-24:00	87	93	86	89	85	86	85	86	84	89	86	92
Max Hour	6	6	6	6	6	6	6	6	6	1	6	6
Min Hour	15	15	12	12	15	12	15	15	12	12	12	12

- Monthly Indicators for Precipitation/Moisture (kPa)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2.6	2.7	2.9	3.2	3.3	3.1	3.0	2.9	2.9	2.9	2.7	2.8

- Monthly Wind Direction % {N=0 or 360,E=90,S=180,W=270}

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
North	28	86	72	70	11	11	79	21	12	30	73	38
NorthEast	43	1	2	0	27	0	0	0	0	2	8	19
East	7	2	2	17	6	0	0	1	0	4	8	4
SouthEast	0	1	1	5	1	2	0	1	0	1	1	0
South	0	0	1	0	1	1	2	1	0	0	1	6
SouthWest	0	1	2	3	26	37	12	33	27	12	2	4
West	3	5	14	4	28	43	7	41	60	46	4	15
NorthWest	19	3	5	0	0	7	0	2	1	5	4	13

- Monthly Statistics for Wind Speed m/s

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maximum	6.4	6.2	7.0	5.2	25.4	6.7	6.7	8.8	7.2	17.0	22.1	15.4
Day:Hour	22:19	28:15	23:18	5:12	11:12	17:15	5:09	25:15	30:21	22:15	8:24	25:12
Minimum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Day:Hour	12:06	1:06	1:04	3:04	2:24	7:06	3:24	1:09	7:06	1:18	2:06	2:06
Daily Avg	2.6	1.9	2.0	1.9	2.4	2.7	2.4	2.1	2.6	1.6	1.6	2.5

- Maximum Wind Speed of 25.4 m/s on May 11
- Minimum Wind Speed of 0.0 m/s on Jan 12

- Average Hourly Statistics for Wind Speed m/s

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01- 1:00	2.2	0.8	0.8	1.3	2.0	2.3	1.7	1.8	2.2	1.1	1.5	1.6
1:01- 2:00	2.1	0.8	0.7	1.2	1.9	2.3	1.8	1.7	2.2	1.0	1.4	1.5
2:01- 3:00	2.0	0.8	0.6	1.1	1.8	2.3	1.8	1.6	2.3	0.9	1.3	1.5
3:01- 4:00	2.0	0.8	0.6	1.0	1.7	2.2	1.8	1.4	2.3	0.8	1.2	1.4
4:01- 5:00	2.0	0.7	0.5	1.0	1.6	2.2	1.9	1.3	2.2	0.8	1.2	1.4
5:01- 6:00	2.0	0.6	0.5	1.0	1.6	2.1	1.9	1.2	2.1	0.9	0.4	1.3
6:01- 7:00	2.2	0.9	0.9	1.2	1.8	2.3	2.1	1.4	2.2	1.0	0.7	1.7
7:01- 8:00	2.4	1.2	1.3	1.4	2.1	2.4	2.3	1.6	2.3	1.2	1.0	2.1
8:01- 9:00	2.6	1.6	1.6	1.6	2.3	2.5	2.4	1.8	2.4	1.4	1.3	2.5
9:01-10:00	2.8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.1	[illegible]	1.7	1.6	2.9
10:01-11:00	2.9	2.3	2.7	2.3	3.1	3.1	2.9	2.4	3.0	2.0	1.8	3.3
11:01-12:00	3.1	2.6	3.3	2.8	3.3	3.3	3.2	2.7	3.2	2.3	2.1	3.7
12:01-13:00	3.1	3.1	[illegible]	2.8	3.4	3.3	3.2	2.8	3.4	2.5	2.1	3.7
13:01-14:00	3.2	3.6	3.8	2.9	3.3	3.3	3.2	2.9	3.5	2.8	2.2	3.7
14:01-15:00	3.3	4.1	4.0	2.9	3.2	3.3	3.2	3.0	3.6	3.1	2.2	3.6
15:01-16:00	3.2	3.7	3.8	2.8	3.0	3.2	3.1	2.8	3.3	2.7	2.1	3.5
16:01-17:00	3.2	3.3	3.6	2.6	2.8	3.0	3.0	2.5	3.0	2.2	2.0	3.4
17:01-18:00	3.1	2.9	3.3	2.6	2.6	2.9	2.9	2.3	2.7	1.8	1.8	3.3
18:01-19:00	3.0	2.4	2.8	2.4	2.4	2.7	2.6	2.3	2.5	1.7	1.8	3.0
19:01-20:00	2.8	1.9	2.3	2.2	2.3	2.7	2.4	2.3	2.3	1.7	1.7	2.7
20:01-21:00	2.6	1.4	1.8	1.9	2.2	2.6	2.1	2.2	2.2	1.6	1.6	2.4
21:01-22:00	2.5	1.2	1.6	1.8	2.1	2.5	2.0	2.2	2.2	1.4	1.6	2.1
22:01-23:00	2.4	1.1	1.3	1.6	2.1	2.4	1.8	2.0	2.3	1.2	1.6	1.9
23:01-24:00	2.2	0.9	1.0	1.4	2.0	2.3	1.6	1.9	2.3	1.1	1.6	1.6
Max Hour	15	15	15	15	12	14	14	15	15	15	15	12
Min Hour	6	6	6	6	6	6	24	6	6	5	6	6

- Average Hourly Statistics for Wind Direction ° {N=0 or 360,E=90,S=180,W=270}

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01- 1:00	101	18	27	32	142	209	30	184	199	138	35	115
1:01- 2:00	101	18	27	32	142	209	30	184	199	138	34	115
2:01- 3:00	91	20	34	27	142	185	30	177	223	135	31	114
3:01- 4:00	91	20	33	27	142	185	30	169	223	135	26	114
4:01- 5:00	91	20	33	27	142	185	30	169	223	135	26	114
5:01- 6:00	98	6	17	24	142	188	46	118	205	105	28	36
6:01- 7:00	98	6	17	24	142	188	46	118	205	105	28	36
7:01- 8:00	98	6	17	24	142	188	46	118	205	105	28	36
8:01- 9:00	65	14	16	30	139	222	41	168	225	157	31	50

9:01-10:00	65	14	16	30	139	222	41	168	225	157	31	61
10:01-11:00	65	14	16	30	139	222	41	168	225	157	31	61
11:01-12:00	113	44	99	54	155	254	58	215	252	212	54	171
12:01-13:00	113	44	99	54	155	254	58	215	252	212	54	171
13:01-14:00	113	44	99	54	155	254	58	215	252	212	54	171
14:01-15:00	128	58	105	62	178	253	59	234	243	224	68	207
15:01-16:00	128	58	105	62	178	253	59	234	243	224	68	207
16:01-17:00	128	58	105	56	178	253	59	234	243	224	68	207
17:01-18:00	152	59	112	50	177	245	60	238	236	220	82	259
18:01-19:00	152	59	112	50	177	245	60	238	236	220	82	259
19:01-20:00	152	59	112	50	177	245	60	238	236	220	82	259
20:01-21:00	127	44	111	50	169	239	53	237	221	217	69	238
21:01-22:00	127	44	111	50	169	239	53	237	221	217	69	238
22:01-23:00	127	44	111	50	169	239	53	237	221	217	69	238
23:01-24:00	100	20	34	35	147	201	30	190	208	140	34	123
Max Hour	18	18	18	15	15	12	18	18	12	15	18	18
Min Hour	9	6	9	6	9	3	1	6	1	6	4	6

- Monthly Statistics for Liquid Precipitation mm

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Total	0	0	0	0	0	0	0	0	0	0	0	0
Max Hourly	0	0	0	0	0	0	0	0	0	0	0	0

- Monthly Statistics for Albedo

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

- Monthly Statistics for Solar Radiation (Direct Normal, Diffuse, Global Horizontal) Wh/m²

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Direct Avg	[illegible]	4937	4984	[illegible]	[illegible]	2776	2726	2847	3115	3188	3314	3693
Direct Max	7250	8161	7327	6571	6003	5487	5231	5717	5565	6484	7108	6547
Day	19	12	1	17	29	13	21	13	23	4	22	25
Diffuse Avg	2268	2364	2583	2786	2868	2849	2861	2972	2848	2768	2631	2359
Global Avg	5387	5909	6364	5704	5248	4932	4935	5198	5324	5145	4955	4859

- Maximum Direct Normal Solar of 8161 Wh/m² on Feb 12

- Average Hourly Statistics for Direct Normal Solar Radiation Wh/m²

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01- 1:00	0	0	0	0	0	0	0	0	0	0	0	0
1:01- 2:00	0	0	0	0	0	0	0	0	0	0	0	0
2:01- 3:00	0	0	0	0	0	0	0	0	0	0	0	0
3:01- 4:00	0	0	0	0	0	0	0	0	0	0	0	0
4:01- 5:00	0	0	0	0	0	0	0	0	0	0	0	0
5:01- 6:00	0	0	0	0	0	0	0	0	0	0	0	0
6:01- 7:00	0	0	2	8	7	7	3	2	4	13	7	1
7:01- 8:00	98	85	156	147	80	98	63	64	82	135	131	105
8:01- 9:00	319	320	389	304	184	200	168	160	206	233	303	305
9:01-10:00	430	462	515	413	256	314	266	254	283	351	356	376
10:01-11:00	541	550	564	455	340	352	288	288	354	349	386	438

11:01-12:00	530	559	574	491	360	325	301	335	428	391	380	467
12:01-13:00	589	575	609	439	366	327	339	355	421	386	433	492
13:01-14:00	542	567	605	432	412	312	328	371	364	430	421	444
14:01-15:00	500	559	545	371	380	303	334	346	374	328	368	401
15:01-16:00	444	498	440	332	315	237	278	301	319	280	287	355
16:01-17:00	348	432	367	253	230	189	206	212	184	196	184	220
17:01-18:00	219	277	183	115	142	93	124	140	90	90	58	85
18:01-19:00	30	54	34	17	26	19	28	19	7	5	1	4
19:01-20:00	0	0	0	0	0	0	0	0	0	0	0	0
20:01-21:00	0	0	0	0	0	0	0	0	0	0	0	0
21:01-22:00	0	0	0	0	0	0	0	0	0	0	0	0
22:01-23:00	0	0	0	0	0	0	0	0	0	0	0	0
23:01-24:00	0	0	0	0	0	0	0	0	0	0	0	0
Max Hour*	13	13	13	12	14	11*	13	14	12	14	13	13
Min Hour	1	1	1	1	1	1	1	1	1	1	1	1

Average Hourly Statistics for Diffuse Horizontal Solar Radiation Wh/m²

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01-1:00	0	0	0	0	0	0	0	0	0	0	0	0
1:01-2:00	0	0	0	0	0	0	0	0	0	0	0	0
2:01-3:00	0	0	0	0	0	0	0	0	0	0	0	0
3:01-4:00	0	0	0	0	0	0	0	0	0	0	0	0
4:01-5:00	0	0	0	0	0	0	0	0	0	0	0	0
5:01-6:00	0	0	0	0	0	0	0	0	0	0	0	0
6:01-7:00	0	0	1	7	12	11	7	6	8	11	8	2
7:01-8:00	50	47	63	79	92	87	77	76	88	86	83	63
8:01-9:00	124	122	139	167	177	157	180	166	184	187	159	137
9:01-10:00	194	209	207	239	257	243	242	259	274	252	243	204
10:01-11:00	245	247	266	292	310	300	320	347	320	324	291	269
11:01-12:00	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	354	315
12:01-13:00	[illegible]	[illegible]	311	341	368	362	[illegible]	385	343	363	359	309
13:01-14:00	[illegible]	309	326	349	365	354	361	370	349	346	344	296
14:01-15:00	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	319	326	324	315	308	300
15:01-16:00	224	247	279	292	278	282	278	285	271	247	250	233
16:01-17:00	183	188	218	201	199	197	206	232	201	178	165	151
17:01-18:00	92	101	122	129	113	128	127	122	102	79	63	74
18:01-19:00	20	31	31	26	28	35	38	33	18	6	3	7
19:01-20:00	0	0	0	0	0	0	0	0	0	0	0	0
20:01-21:00	0	0	0	0	0	0	0	0	0	0	0	0
21:01-22:00	0	0	0	0	0	0	0	0	0	0	0	0
22:01-23:00	0	0	0	0	0	0	0	0	0	0	0	0
23:01-24:00	0	0	0	0	0	0	0	0	0	0	0	0
Max Hour	14	14	14	13	13	12	14	13	13	12	13	12
Min Hour	1	1	1	1	1	1	1	1	1	1	1	1

Average Hourly Statistics for Global Horizontal Solar Radiation Wh/m²

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01-1:00	0	0	0	0	0	0	0	0	0	0	0	0
1:01-2:00	0	0	0	0	0	0	0	0	0	0	0	0
2:01-3:00	0	0	0	0	0	0	0	0	0	0	0	0
3:01-4:00	0	0	0	0	0	0	0	0	0	0	0	0
4:01-5:00	0	0	0	0	0	0	0	0	0	0	0	0
5:01-6:00	0	0	0	0	0	0	0	0	0	0	0	0
6:01-7:00	0	0	1	8	12	11	7	6	8	11	9	2
7:01-8:00	62	58	90	112	112	111	91	90	107	119	112	80
8:01-9:00	236	240	302	309	265	250	255	240	282	300	294	255
9:01-10:00	433	478	534	519	431	451	415	428	468	492	470	422
10:01-11:00	634	663	722	675	594	587	553	587	621	616	593	589

11:01-12:00	727	793	844	785	682	666	626	681	754	740	685	701
12:01-13:00	808	833	910	798	725	675	686	737	783	734	750	735
13:01-14:00	765	838	913	770	756	647	673	730	701	742	708	670
14:01-15:00	671	745	795	657	656	588	611	634	652	585	590	604
15:01-16:00	522	610	610	538	506	453	484	511	503	432	426	453
16:01-17:00	354	424	424	340	321	299	321	350	298	268	242	248
17:01-18:00	153	190	183	166	157	158	170	169	128	99	74	93
18:01-19:00	22	37	35	28	30	37	41	34	19	6	3	7
19:01-20:00	0	0	0	0	0	0	0	0	0	0	0	0
20:01-21:00	0	0	0	0	0	0	0	0	0	0	0	0
21:01-22:00	0	0	0	0	0	0	0	0	0	0	0	0
22:01-23:00	0	0	0	0	0	0	0	0	0	0	0	0
23:01-24:00	0	0	0	0	0	0	0	0	0	0	0	0
Max Hour	13	14	14	13	14	13	13	13	13	14	13	13
Min Hour	1	1	1	1	1	1	1	1	1	1	1	1

Average Hourly Statistics for Total Sky Cover %

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01- 1:00	39	50	49	56	65	70	65	70	67	60	69	59
1:01- 2:00	38	49	46	55	65	71	66	71	67	61	65	57
2:01- 3:00	39	48	42	55	67	73	70	71	69	61	62	57
3:01- 4:00	39	46	39	54	69	74	70	71	72	60	61	55
4:01- 5:00	38	42	34	53	69	76	71	70	76	61	61	52
5:01- 6:00	39	40	32	53	71	80	74	71	80	62	63	49
6:01- 7:00	40	41	31	54	[illegible]	78	73	72	78	64	62	46
7:01- 8:00	41	41	32	56	75	75	74	75	77	67	63	45
8:01- 9:00	42	[illegible]	[illegible]	59	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	70	64	45
9:01-10:00	45	43	36	60	75	74	75	77	73	71	65	49
10:01-11:00	47	44	39	62	74	74	77	75	69	71	67	52
11:01-12:00	54	48	43	64	72	76	80	76	68	73	70	56
12:01-13:00	54	45	44	65	73	76	78	75	68	73	69	55
13:01-14:00	55	44	46	67	73	78	75	75	70	73	69	55
14:01-15:00	57	45	49	70	74	80	75	75	73	75	69	58
15:01-16:00	56	46	53	73	74	82	75	75	75	75	72	61
16:01-17:00	57	47	57	73	75	83	77	77	81	78	77	67
17:01-18:00	59	49	63	79	77	85	79	79	84	80	81	73
18:01-19:00	53	47	59	76	72	82	75	78	78	75	80	71
19:01-20:00	50	44	56	72	68	79	72	76	72	72	76	69
20:01-21:00	47	43	54	71	64	76	70	74	68	69	75	67
21:01-22:00	44	44	53	66	64	72	68	73	68	66	71	65
22:01-23:00	41	45	53	62	61	70	66	73	68	64	70	64
23:01-24:00	38	48	53	59	62	70	65	72	69	63	68	64
Max Hour	18	1	18	18	9	18	12	18	18	18	18	18
Min Hour	2	9	7	5	23	24	1	1	1	4	4	9

- Average Hourly Statistics for Opaque Sky Cover %

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01- 1:00	33	44	42	51	61	63	62	63	63	55	58	52
1:01- 2:00	33	42	38	49	61	66	63	65	64	55	54	51
2:01- 3:00	32	42	35	48	64	68	65	66	65	55	51	48
3:01- 4:00	32	39	31	45	65	68	65	65	67	55	51	47
4:01- 5:00	33	38	27	45	66	69	66	64	68	54	52	44
5:01- 6:00	33	35	25	43	66	70	69	64	70	54	51	41
6:01- 7:00	33	36	25	45	68	68	69	64	69	56	51	41

7:01- 8:00	34	35	26	46	69	66	68	67	67	58	51	41
8:01- 9:00	34	35	28	48	71	64	68	69	67	63	52	41
9:01-10:00	38	36	31	50	69	64	70	68	64	63	54	45
10:01-11:00	41	39	34	52	67	64	71	65	62	65	57	48
11:01-12:00	46	42	38	53	65	65	72	65	59	65	60	52
12:01-13:00	47	40	39	56	65	67	70	65	62	64	58	52
13:01-14:00	47	39	42	58	65	68	69	65	63	64	58	52
14:01-15:00	49	39	43	61	65	69	68	66	65	63	57	54
15:01-16:00	47	40	46	63	67	71	69	65	69	65	62	56
16:01-17:00	48	40	51	65	66	71	68	66	72	66	66	62
17:01-18:00	47	40	55	70	67	72	70	67	75	68	71	66
18:01-19:00	44	38	53	68	64	70	69	66	71	65	70	64
19:01-20:00	41	35	49	66	60	69	67	65	68	64	67	64
20:01-21:00	38	33	47	64	57	66	65	64	64	61	63	62
21:01-22:00	36	36	47	61	56	63	65	65	64	59	62	61
22:01-23:00	33	39	48	58	56	61	63	64	63	58	60	58
23:01-24:00	33	41	47	55	57	61	62	64	64	56	58	57
Max Hour	15	1	18	18	9	18	12	9	18	18	18	18
Min Hour	4	21	6	6	23	23	1	1	12	5	3	6

- Monthly Calculated "undisturbed" Ground Temperatures** °C

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0.5 m	26.5	26.1	26.0	26.1	26.7	27.3	27.9	28.4	28.5	28.3	27.8	27.2
2.0 m	26.9	26.5	26.3	26.3	26.6	27.1	27.5	28.0	28.2	28.1	27.9	27.4
4.0 m	27.2	26.9	26.7	26.6	26.7	27.0	27.3	27.6	27.8	27.9	27.8	27.5

- **These ground temperatures should NOT BE USED in the GroundTemperatures object to compute building floor losses.
- The temperatures for 0.5 m depth can be used for GroundTemperatures:Surface.
- The temperatures for 4.0 m depth can be used for GroundTemperatures:Deep.
- Calculations use a standard soil diffusivity of 2.3225760E-03 {m**2/day}

- 6299 annual (wthr file) cooling degree-days (10°C baseline)
- 0 annual (wthr file) heating degree-days (10°C baseline)

- 3379 annual (wthr file) cooling degree-days (18°C baseline)
- 0 annual (wthr file) heating degree-days (18°C baseline)

- Climate type "Af" (Köppen classification)**
- Tropical wet (no dry season, rainforest, hot all year, lat. < 10°)
- Heating may not be required
- **Note that the Köppen classification shown here is derived algorithmically from the source weather data.
- It may not be indicative of the long term climate for this location.

- Climate type "1A" (ASHRAE Standard 196-2006 Climate Zone)**
- Very Hot - Humid, Probable Köppen classification=Aw, Tropical Wet-and-Dry
- **Note that the ASHRAE classification shown here is derived algorithmically from the source weather data.

Colombo – Katunayake regional data - Rural simulation.

-EnergyPlus Weather Converter V7.1.0.010
Statistics for LKA_Colombo-Katunayake.434500_SWERA
Location -- COLOMBO/KATUNAYAKE - LKA
{N 7° 10'} {E 79° 52'} {GMT +6.0 Hours}
Elevation -- 8m above sea level
Standard Pressure at Elevation -- 101229Pa
Data Source -- SWERA

WMO Station 434500

- Monthly Drybulb and Mean Coincident Wetbulb Temperatures °C

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Drybulb 0.4%	33.4	35	34	33.2	32.9	31.9	31	31.2	31.2	31.2	32.2	32.9
Coincident Wetbulb 0.4%	23.3	23.4	25.1	27	27.6	27.3	26.5	25.8	26	25.9	24.6	23.5
Drybulb 2.0%	32.2	33.1	32.9	32.8	32.2	31.1	30.2	30.8	31	30.9	31.1	31.7
Coincident Wetbulb 2.0%	23.4	23.6	25.7	26.8	27.3	26.9	26.1	26	26	25.9	25	23.8
Drybulb 5.0%	31.6	32.1	32.2	32.1	31.8	30.7	30	30.1	30.3	30.2	30.3	31
Coincident Wetbulb 5.0%	23.5	24	25.8	26.6	27.2	26.7	26	25.9	25.8	25.8	25.3	24.1
Drybulb 10.%	30.8	31.2	31.7	31.7	31.1	30.1	29.6	29.8	30	29.9	29.8	30.1
Coincident Wetbulb 10%	23.7	24.4	25.7	26.5	27	26.4	25.8	25.8	25.7	25.7	25.3	24.3

- Monthly Drybulb and Wetbulb Daily Ranges delta°C

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Drybulb	8.6	8.9	7.7	6.8	4.9	3.9	3.7	4.0	4.6	5.2	6.2	7.2
Drybulb range - DB 5%	9.6	9.9	8.2	7.2	5.5	4.5	3.9	4.4	4.9	5.7	7.1	8.7
Wetbulb range - DB 5%	3.2	3.5	3.1	2.7	2.3	1.9	1.8	1.8	1.9	2.4	2.7	3.0

Drybulb = Mean Daily Dry Bulb Temperature Range
Drybulb range - DB 5% = Mean Daily Dry Bulb Temperature Range Coincident with 5% Design Dry Bulb Temperature
Wetbulb range - DB 5% = Mean Daily Wet Bulb Temperature Range Coincident with 5% Design Dry Bulb Temperature

- Monthly Statistics for Dry Bulb temperatures °C

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maximum	35.0	38.0	34.0	48.0	33.0	31.3	31.0	32.0	32.0	33.0	32.0	33.1
Day:Hour	20:15	23:15	2:15	25:21	9:12	20:12	1:15	4:12	5:14	30:21	1:12	3:15
Minimum	19.0	21.0	21.0	21.0	23.8	24.4	23.8	24.0	23.4	21.6	22.6	20.0
Day:Hour	15:05	2:06	14:06	30:06	19:01	25:24	23:11	14:22	11:06	26:06	25:06	14:24
Daily Avg	26.8	26.9	27.8	28.3	28.4	27.9	27.6	27.4	27.3	27.0	26.6	26.4

- Maximum Dry Bulb temperature of 48.0°C on Apr 25
- Minimum Dry Bulb temperature of 19.0°C on Jan 15

- Monthly Statistics for Dew Point temperatures °C

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maximum	26.0	25.0	26.0	27.0	27.0	26.4	26.7	25.6	27.0	31.0	25.6	25.0
Day:Hour	25:20	4:15	5:18	10:12	26:12	26:15	16:09	14:12	14:09	30:21	12:18	6:12
Minimum	15.0	-0.7	11.0	10.9	21.6	21.0	22.0	21.7	22.6	12.0	20.0	11.0
Day:Hour	13:13	13:24	15:12	30:06	17:18	4:04	12:15	26:19	17:24	7:24	15:14	14:24
Daily Avg	21.6	20.6	22.7	24.3	25.0	24.2	24.3	23.9	24.3	23.8	23.3	22.4

- Maximum Dew Point temperature of 31.0°C on Oct 30
- Minimum Dew Point temperature of -0.7°C on Feb 13

- Average Hourly Statistics for Dry Bulb temperatures °C

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01- 1:00	24.5	24.7	25.5	26.6	26.9	27.0	26.6	26.3	26.0	25.6	24.9	24.4
1:01- 2:00	24.1	24.3	25.1	26.2	26.7	26.8	26.4	26.2	25.8	25.4	24.8	24.2
2:01- 3:00	23.7	23.9	24.6	25.9	26.5	26.7	26.2	26.1	25.6	25.2	24.5	24.1
3:01- 4:00	23.3	23.5	24.4	25.6	26.4	26.6	26.1	26.0	25.6	25.0	24.2	23.9
4:01- 5:00	23.0	23.1	24.2	25.4	26.1	26.5	26.1	26.0	25.4	24.9	24.1	23.6
5:01- 6:00	22.7	22.7	24.0	25.2	26.0	26.4	26.1	25.9	25.3	24.7	23.9	23.4
6:01- 7:00	23.2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	25.4	24.8	24.3
7:01- 8:00	[illegible]	24.0	26.1	27.2	27.6	[illegible]	27.0	27.0	26.8	26.3	25.8	25.3
8:01- 9:00	[illegible]	24.8	27.1	28.2	28.6	28.0	[illegible]	[illegible]	[illegible]	27.3	27.0	26.2
9:01-10:00	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	28.6	28.3	28.2	28.2	28.0	28.1	27.3
10:01-11:00	29.4	28.8	30.1	30.1	30.2	29.0	28.8	28.8	28.9	28.7	29.1	28.4
11:01-12:00	30.5	30.6	31.5	31.0	31.0	29.4	29.2	29.4	29.4	29.3	29.8	29.5
12:01-13:00	30.8	30.9	31.5	31.2	31.0	29.4	29.3	29.3	29.4	29.4	29.7	29.5
13:01-14:00	30.8	31.2	31.6	31.4	30.9	29.3	29.3	29.2	29.2	29.5	29.5	29.6
14:01-15:00	30.6	31.4	31.6	31.6	30.9	29.2	29.1	29.1	29.0	29.6	29.1	29.6
15:01-16:00	30.2	30.6	31.1	30.9	30.3	29.0	28.7	28.7	28.7	28.9	28.5	29.0
16:01-17:00	29.8	29.8	30.5	30.3	29.8	28.7	28.5	28.3	28.4	28.3	27.8	28.4
17:01-18:00	29.3	28.9	30.0	29.5	29.3	28.5	28.2	27.9	28.1	27.7	27.2	27.8
18:01-19:00	28.2	28.3	29.2	29.1	28.9	28.3	27.8	27.6	27.7	27.3	26.7	27.2
19:01-20:00	27.3	27.8	28.5	28.7	28.5	28.1	27.5	27.4	27.3	26.9	26.3	26.6
20:01-21:00	26.6	27.2	27.8	28.3	28.2	27.8	27.3	27.0	26.9	26.6	26.0	26.0
21:01-22:00	26.0	26.6	27.1	27.9	27.8	27.6	27.2	26.8	26.6	26.3	25.6	25.5
22:01-23:00	25.3	25.9	26.6	27.5	27.4	27.3	26.9	26.7	26.4	26.0	25.3	25.1
23:01-24:00	24.9	25.2	25.9	27.0	27.1	27.1	26.7	26.5	26.1	25.8	25.0	24.6
Max Hour	14	15	15	15	12	12	13	12	12	15	12	15
Min Hour	6	6	6	6	6	6	6	6	6	6	6	6

- Average Hourly Statistics for Dew Point temperatures °C

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01- 1:00	21.9	20.2	22.5	24.1	24.9	24.1	24.4	24.0	24.3	23.6	23.3	22.5
1:01- 2:00	21.8	20.0	22.6	24.0	24.9	24.1	24.3	23.9	24.3	23.6	23.3	22.5
2:01- 3:00	21.7	19.8	22.6	23.8	24.9	24.0	24.2	23.9	24.2	23.7	23.2	22.6
3:01- 4:00	21.6	19.6	22.5	23.6	24.9	24.0	24.3	23.8	24.1	23.7	23.2	22.4
4:01- 5:00	21.6	19.6	22.4	23.4	24.8	24.0	24.2	23.8	24.0	23.6	23.1	22.3

5:01- 6:00	21.4	19.6	22.3	23.2	24.8	23.9	24.1	23.8	24.0	23.5	23.1	22.2
6:01- 7:00	21.5	19.9	22.5	23.6	24.9	24.0	24.4	23.8	24.1	23.6	23.2	22.3
7:01- 8:00	21.6	20.2	22.7	23.9	25.1	24.1	24.4	23.9	24.3	23.9	23.3	22.5
8:01- 9:00	21.7	20.5	22.9	24.3	25.1	24.2	24.6	24.0	24.4	24.0	23.5	22.6
9:01-10:00	21.7	20.5	22.6	24.5	25.1	24.4	24.5	24.0	24.4	24.0	23.4	22.5
10:01-11:00	21.4	20.5	22.4	24.8	25.1	24.4	24.5	24.0	24.4	24.0	23.2	22.3
11:01-12:00	21.3	20.6	22.2	25.1	25.1	24.5	24.5	24.1	24.4	24.0	23.2	22.2
12:01-13:00	21.1	20.6	22.3	25.0	25.1	24.5	24.5	24.1	24.4	24.0	23.2	22.2
13:01-14:00	21.2	20.8	22.5	25.0	25.1	24.5	24.5	24.0	24.4	24.1	23.3	22.2
14:01-15:00	21.1	20.8	22.6	25.0	25.2	24.4	24.4	24.0	24.4	24.1	23.3	22.2
15:01-16:00	20.9	21.1	22.7	24.8	25.1	24.4	24.4	24.0	24.4	24.0	23.4	22.3
16:01-17:00	21.2	21.3	22.8	24.5	25.0	24.3	24.3	23.9	24.4	23.9	23.4	22.5
17:01-18:00	21.5	21.5	22.9	24.3	24.9	24.3	24.2	23.8	24.4	23.7	23.5	22.6
18:01-19:00	21.8	21.6	23.0	24.3	24.9	24.3	24.2	23.8	24.3	23.7	23.4	22.6
19:01-20:00	22.0	21.6	23.0	24.3	24.9	24.2	24.1	23.9	24.3	23.8	23.4	22.6
20:01-21:00	21.9	21.5	23.1	24.3	24.9	24.2	24.2	23.9	24.2	23.9	23.5	22.6
21:01-22:00	21.9	21.1	22.9	24.3	24.9	24.2	24.2	24.0	24.2	23.8	23.4	22.5
22:01-23:00	21.9	20.7	22.8	24.3	25.0	24.1	24.3	24.0	24.3	23.7	23.3	22.5
23:01-24:00	21.9	20.4	22.7	24.3	25.0	24.1	24.3	24.0	24.3	23.5	23.3	22.4
Max Hour	20	19	21	12	15	12	9	12	10	15	9	9
Min Hour	16	6	12	6	6	6	20	6	6	6	6	12

- Monthly Statistics for Relative Humidity %

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maximum	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	100	100	100
Day:Hour	[illegible]	8:06	27:0[illegible]	1:06	5:06	9:06	5:03	14:22	6:03	10:07	1:21	2:06
Minimum	34	23	26	28	61	66	63	59	63	44	49	46
Day:Hour	30:15	13:24	15:12	10:09	2:12	4:15	4:14	4:15	5:14	7:24	15:14	15:12
Daily Avg	75	70	75	80	82	81	83	82	84	83	83	80

- Average Hourly Relative Humidity %

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01- 1:00	86	77	84	87	89	84	88	87	91	89	91	90
1:01- 2:00	87	78	86	88	90	85	88	87	91	90	92	91
2:01- 3:00	89	79	89	89	91	86	89	88	92	91	93	91
3:01- 4:00	90	80	89	89	92	86	90	88	92	93	94	92
4:01- 5:00	92	81	90	90	93	86	90	88	92	93	95	92
5:01- 6:00	93	83	91	90	93	87	89	88	92	93	95	93
6:01- 7:00	90	82	86	87	90	84	88	86	90	90	91	89
7:01- 8:00	86	80	82	83	86	82	86	84	87	87	86	85
8:01- 9:00	78	78	78	81	82	80	84	81	83	83	82	81
9:01-10:00	69	69	70	77	78	78	80	78	80	79	76	75
10:01-11:00	62	61	64	74	74	76	77	76	77	76	71	70
11:01-12:00	59	56	59	71	71	75	76	73	75	73	68	66
12:01-13:00	58	55	59	70	71	75	76	74	75	73	69	65
13:01-14:00	58	54	59	69	72	76	76	74	76	73	70	65
14:01-15:00	58	54	59	69	72	76	76	74	76	73	72	65

15:01-16:00	59	57	61	70	74	77	78	76	78	75	74	68
16:01-17:00	61	61	64	71	76	77	78	77	79	77	77	71
17:01-18:00	64	65	67	74	78	78	79	78	80	79	81	74
18:01-19:00	69	68	70	76	79	79	81	80	82	82	83	76
19:01-20:00	74	70	73	78	81	80	82	81	84	83	84	79
20:01-21:00	76	72	76	80	83	81	83	83	85	86	86	82
21:01-22:00	79	73	78	82	85	82	84	84	87	87	88	84
22:01-23:00	82	75	80	84	87	83	86	85	88	88	89	86
23:01-24:00	83	77	83	86	88	84	87	87	90	88	90	88
Max Hour	6	6	6	6	6	6	4	6	6	6	6	6
Min Hour	13	15	12	15	12	12	13	12	12	14	12	14

Monthly Indicators for Precipitation/Moisture (kPa)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2.5	2.5	2.8	3.2	3.2	3.1	3.1	3.0	3.1	3.0	2.9	2.7

Monthly Wind Direction % {N=0 or 360,E=90,S=180,W=270}

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
North	36	54	56	56	18	7	10	10	20	34	37	54
NorthEast	31	13	4	1	1	0	0	0	0	2	13	18
East	6	1	3	2	1	0	0	0	0	2	8	4
SouthEast	5	0	1	3	7	4	2	2	5	5	4	4
South	1	0	0	2	20	8	5	5	11	7	2	1
SouthWest	1	5	8	14	23	46	35	44	36	13	12	5
West	9	21	25	19	29	33	46	39	26	32	19	9
NorthWest	12	5	2	3	2	3	2	0	1	4	7	5

- Average Hourly Statistics for Wind Speed m/s

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01- 1:00	2.2	2.3	0.2	0.4	2.3	3.3	4.0	3.6	2.1	1.6	1.2	1.2
1:01- 2:00	2.3	2.1	0.1	0.3	2.3	3.2	3.6	3.5	2.1	1.5	1.0	1.1
2:01- 3:00	2.4	1.8	0.1	0.2	2.2	3.1	3.4	3.4	2.0	1.5	0.8	1.1
3:01- 4:00	2.2	1.6	0.1	0.1	2.2	2.9	3.5	3.5	2.2	1.5	1.1	1.2
4:01- 5:00	2.0	1.3	0.0	0.1	2.2	2.9	3.4	3.5	2.1	1.5	0.9	1.2
5:01- 6:00	1.8	1.1	0.0	0.1	2.2	2.9	3.1	3.6	2.1	1.6	0.8	1.3
6:01- 7:00	2.3	1.1	0.5	0.2	2.5	3.2	3.6	3.9	2.9	1.7	0.8	1.8
7:01- 8:00	2.7	1.2	1.0	0.4	2.7	3.5	4.2	4.2	3.9	2.4	1.7	2.4
8:01- 9:00	3.1	1.2	1.4	0.5	3.1	3.8	5.0	4.6	4.7	2.8	2.0	2.9
9:01-10:00	3.7	1.9	2.3	1.5	3.7	4.1	5.6	4.9	5.6	3.4	2.6	3.3
10:01-11:00	4.4	2.7	3.2	2.5	4.1	4.4	6.0	5.3	6.4	3.8	3.2	3.6
11:01-12:00	4.9	3.6	4.1	3.5	4.6	4.6	6.5	5.6	7.0	4.3	3.8	3.9
12:01-13:00	4.9	3.9	4.4	3.7	4.9	4.6	6.4	5.8	6.8	4.5	4.3	3.9
13:01-14:00	5.0	4.3	4.7	3.9	5.3	4.7	6.7	5.9	6.6	5.0	4.4	3.9
14:01-15:00	5.1	4.8	5.0	4.1	5.7	4.8	6.9	6.1	6.1	5.2	4.3	3.9
15:01-16:00	5.1	4.5	4.7	3.7	5.8	4.6	6.2	6.0	5.6	4.8	4.0	3.6
16:01-17:00	4.9	4.0	4.3	3.3	5.8	4.4	5.8	5.4	5.0	4.4	3.5	3.4
17:01-18:00	4.7	3.7	4.0	2.8	5.7	4.1	5.3	4.9	4.4	4.2	3.2	3.1
18:01-19:00	4.0	2.9	3.1	2.4	5.1	4.0	5.0	4.6	3.9	3.4	2.4	2.7
19:01-20:00	3.4	2.2	2.3	2.1	4.5	3.9	4.8	4.4	3.5	2.8	2.2	2.3
20:01-21:00	3.2	1.7	1.4	1.7	3.9	3.7	4.6	4.1	3.2	2.3	1.9	1.9
21:01-22:00	3.1	2.0	1.0	1.3	3.3	3.6	4.4	4.1	2.8	2.2	1.8	1.7
22:01-23:00	2.8	2.4	0.6	0.9	2.8	3.6	4.1	3.9	2.5	1.8	1.4	1.5
23:01-24:00	2.4	2.6	0.2	0.6	2.2	3.5	4.1	3.7	2.1	1.6	1.3	1.3
Max Hour	15	15	15	15	16	15	15	15	12	15	14	12
Min Hour	6	6	6	6	4	6	6	3	3	4	7	3

- Average Hourly Statistics for Wind Direction ° {N=0 or 360,E=90,S=180,W=270}

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01- 1:00	71	72	13	33	117	195	188	182	128	116	50	27
1:01- 2:00	45	65	13	33	116	203	189	182	114	116	41	27
2:01- 3:00	46	61	12	26	111	190	188	163	116	99	30	20
3:01- 4:00	49	39	12	23	118	189	190	163	124	103	36	20
4:01- 5:00	44	40	12	23	117	189	195	163	120	101	34	20
5:01- 6:00	29	4	0	5	122	177	175	180	111	55	41	12
6:01- 7:00	28	4	0	5	115	177	185	188	116	54	35	12
7:01- 8:00	36	4	0	5	121	176	179	189	116	60	52	12
8:01- 9:00	57	10	15	27	152	204	207	215	130	111	66	37
9:01-10:00	73	9	15	27	161	204	208	215	141	111	87	37
10:01-11:00	99	17	15	27	159	204	221	218	167	119	87	37
11:01-12:00	149	138	185	193	236	237	245	243	217	221	185	125
12:01-13:00	153	139	185	193	235	237	247	242	219	221	194	125
13:01-14:00	146	139	185	193	237	238	248	242	226	220	208	125
14:01-15:00	183	179	204	206	242	228	245	241	227	250	204	165
15:01-16:00	179	178	204	206	242	228	247	240	226	249	215	165
16:01-17:00	186	179	204	207	244	228	247	240	224	247	216	165
17:01-18:00	208	182	226	180	228	243	226	238	233	208	211	183
18:01-19:00	216	183	226	180	226	243	227	236	235	206	212	183
19:01-20:00	201	186	226	180	218	243	225	234	236	203	171	183
20:01-21:00	210	147	142	137	207	242	217	219	228	174	158	123
21:01-22:00	198	135	142	137	213	242	210	222	228	173	161	123
22:01-23:00	168	137	142	137	212	242	198	222	230	167	146	123
23:01-24:00	84	60	13	51	119	210	189	192	126	103	57	28
Max Hour	19	20	18	17	17	18	14	12	20	15	17	18
Min Hour	7	6	6	6	7	6	6	4	6	7	3	6

- Monthly Statistics for Solar Radiation (Direct Normal, Diffuse, Global Horizontal) Wh/m²

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Direct Avg	4620	5005	5165	4067	3116	2661	2730	2658	3120	3235	3575	4255
Direct Max	7496	7647	7580	6928	5398	4934	4889	5525	5559	5273	6831	7736
Day	19	18	17	16	12	12	28	9	29	22	11	23
Diffuse Avg	2293	2407	2500	2786	2892	2921	2907	3090	2926	2806	2536	2233
Global Avg	5424	6016	6344	5947	5291	4948	5026	5178	5357	5225	5012	5024

- Maximum Direct Normal Solar of 7736 Wh/m² on Dec 23

- Average Hourly Statistics for Direct Normal Solar Radiation Wh/m²

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01- 1:00	0	0	0	0	0	0	0	0	0	0	0	0
1:01- 2:00	0	0	0	0	0	0	0	0	0	0	0	0
2:01- 3:00	0	0	0	0	0	0	0	0	0	0	0	0
3:01- 4:00	0	0	0	0	0	0	0	0	0	0	0	0
4:01- 5:00	0	0	0	0	0	0	0	0	0	0	0	0
5:01- 6:00	0	0	0	0	0	0	0	0	0	0	0	0
6:01- 7:00	0	0	3	6	8	4	2	2	5	10	11	3
7:01- 8:00	88	107	166	167	116	74	63	65	108	123	169	131

8:01-9:00	318	352	428	315	247	131	165	160	247	267	313	332
9:01-10:00	481	489	522	424	303	249	248	240	368	400	392	434
10:01-11:00	524	529	531	469	325	282	334	292	420	385	423	497
11:01-12:00	483	569	546	499	394	336	350	338	352	368	434	477
12:01-13:00	574	597	575	518	383	340	296	354	372	420	447	511
13:01-14:00	570	620	593	482	363	339	381	340	398	377	398	503
14:01-15:00	527	580	580	423	349	299	323	301	311	372	382	453
15:01-16:00	486	517	515	370	339	267	269	242	272	269	325	398
16:01-17:00	361	385	426	256	184	188	189	194	177	169	191	337
17:01-18:00	184	220	242	121	92	129	92	114	80	73	87	165
18:01-19:00	24	39	36	18	14	22	17	16	10	2	2	13
19:01-20:00	0	0	0	0	0	0	0	0	0	0	0	0
20:01-21:00	0	0	0	0	0	0	0	0	0	0	0	0
21:01-22:00	0	0	0	0	0	0	0	0	0	0	0	0
22:01-23:00	0	0	0	0	0	0	0	0	0	0	0	0
23:01-24:00	0	0	0	0	0	0	0	0	0	0	0	0
Max Hour*	13	14	14	13	12	13	14	13	11*	13	13	13
Min Hour	1	1	1	1	1	1	1	1	1	1	1	1

Average Hourly Statistics for Diffuse Horizontal Solar Radiation Wh/m²

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01-1:00	0	0	0	0	0	0	0	0	0	0	0	0
1:01-2:00	0	0	0	0	0	0	0	0	0	0	0	0
2:01-3:00	0	0	0	0	0	0	0	0	0	0	0	0
3:01-4:00	0	0	0	0	0	0	0	0	0	0	0	0
4:01-5:00	0	0	0	0	0	0	0	0	0	0	0	0
5:01-6:00	0	0	0	0	0	0	0	0	0	0	0	0
6:01-7:00	0	0	1	7	13	11	7	6	8	11	7	2
7:01-8:00	[illegible]	46	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	77	58
8:01-9:00	[illegible]	123	137	164	168	174	175	159	199	194	158	134
9:01-10:00	[illegible]	198	206	237	264	263	257	271	255	237	249	208
10:01-11:00	[illegible]	256	260	[illegible]	[illegible]	[illegible]	303	327	307	329	306	253
11:01-12:00	311	311	317	342	345	348	346	394	378	351	326	276
12:01-13:00	301	308	333	354	371	372	360	401	375	370	327	292
13:01-14:00	289	301	303	350	368	373	354	399	337	377	327	294
14:01-15:00	274	287	287	340	316	331	335	363	353	314	298	263
15:01-16:00	225	252	243	273	269	288	286	304	295	253	252	224
16:01-17:00	174	180	207	199	213	200	230	224	212	198	144	151
17:01-18:00	98	115	114	115	114	107	136	129	101	76	62	71
18:01-19:00	19	31	31	29	27	34	40	33	19	6	3	7
19:01-20:00	0	0	0	0	0	0	0	0	0	0	0	0
20:01-21:00	0	0	0	0	0	0	0	0	0	0	0	0
21:01-22:00	0	0	0	0	0	0	0	0	0	0	0	0
22:01-23:00	0	0	0	0	0	0	0	0	0	0	0	0
23:01-24:00	0	0	0	0	0	0	0	0	0	0	0	0
Max Hour	12	12	13	13	13	14	13	13	12	14	14	14
Min Hour	1	1	1	1	1	1	1	1	1	1	1	1

Average Hourly Statistics for Global Horizontal Solar Radiation Wh/m²

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01-1:00	0	0	0	0	0	0	0	0	0	0	0	0
1:01-2:00	0	0	0	0	0	0	0	0	0	0	0	0
2:01-3:00	0	0	0	0	0	0	0	0	0	0	0	0
3:01-4:00	0	0	0	0	0	0	0	0	0	0	0	0
4:01-5:00	0	0	0	0	0	0	0	0	0	0	0	0
5:01-6:00	0	0	0	0	0	0	0	0	0	0	0	0
6:01-7:00	0	0	1	8	13	11	7	6	9	11	8	2

7:01- 8:00	54	60	89	119	116	106	91	94	115	122	115	79
8:01- 9:00	228	252	316	312	288	236	249	232	318	323	298	262
9:01-10:00	453	482	537	524	471	430	419	430	508	510	500	459
10:01-11:00	629	655	690	691	611	561	575	569	665	650	638	615
11:01-12:00	710	809	823	817	715	657	668	713	713	693	705	670
12:01-13:00	806	864	899	870	745	699	647	751	745	772	730	733
13:01-14:00	784	875	879	820	715	692	718	730	721	723	672	715
14:01-15:00	693	783	804	716	619	588	618	632	625	618	590	606
15:01-16:00	548	627	631	548	515	481	487	486	492	430	451	470
16:01-17:00	350	388	446	339	311	303	337	334	304	275	223	297
17:01-18:00	148	185	194	153	143	149	168	167	124	92	79	108
18:01-19:00	21	35	35	31	29	36	42	35	20	6	3	7
19:01-20:00	0	0	0	0	0	0	0	0	0	0	0	0
20:01-21:00	0	0	0	0	0	0	0	0	0	0	0	0
21:01-22:00	0	0	0	0	0	0	0	0	0	0	0	0
22:01-23:00	0	0	0	0	0	0	0	0	0	0	0	0
23:01-24:00	0	0	0	0	0	0	0	0	0	0	0	0
Max Hour	13	14	13	13	13	13	14	13	13	13	13	13
Min Hour	1	1	1	1	1	1	1	1	1	1	1	1

- Average Hourly Statistics for Total Sky Cover %

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01- 1:00	38	34	45	60	75	74	70	74	61	67	64	37
1:01- 2:00	35	31	39	56	72	75	71	76	59	66	63	39
2:01- 3:00	34	31	35	53	69	75	71	77	58	67	60	39
3:01- 4:00	35	29	32	51	68	75	72	77	58	68	61	36
4:01- 5:00	29	25	30	50	67	76	73	76	58	68	61	35
5:01- 6:00	27	23	29	51	67	79	75	76	62	71	61	35
6:01- 7:00	34	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	59	38
7:01- 8:00	[illegible]	[illegible]	29	49	68	76	75	76	61	65	59	42
8:01- 9:00	[illegible]	34	30	53	70	76	76	77	63	65	58	47
9:01-10:00	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	74	76	75	62	61	57	49
10:01-11:00	43	40	41	56	68	73	74	74	63	67	62	53
11:01-12:00	55	47	48	59	69	73	75	74	71	69	66	55
12:01-13:00	46	44	45	59	69	72	76	73	70	67	63	54
13:01-14:00	46	43	42	59	71	73	76	73	71	67	63	55
14:01-15:00	52	44	41	60	70	73	78	75	74	68	65	54
15:01-16:00	47	46	45	62	73	74	80	75	76	71	68	53
16:01-17:00	48	52	49	68	76	74	83	77	79	75	71	52
17:01-18:00	60	59	55	73	82	76	87	81	82	77	79	52
18:01-19:00	47	56	55	71	78	74	83	79	73	75	74	48
19:01-20:00	45	52	57	67	78	74	81	77	71	77	72	45
20:01-21:00	42	51	58	65	77	73	78	75	68	75	69	44
21:01-22:00	40	47	54	62	78	73	76	74	67	73	69	41
22:01-23:00	38	45	51	62	77	74	74	74	66	68	70	38
23:01-24:00	47	41	49	62	76	74	71	74	66	67	70	37
Max Hour	18	18	21	18	18	6	18	18	18	18	18	12
Min Hour	6	6	7	8	7	13	1	13	3	10	10	6

- Average Hourly Statistics for Opaque Sky Cover %

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01- 1:00	33	28	39	55	68	71	65	69	58	63	61	30
1:01- 2:00	29	26	35	52	66	71	67	72	56	62	58	31
2:01- 3:00	28	25	31	47	65	72	68	73	56	62	54	32
3:01- 4:00	30	23	29	45	62	73	68	74	55	62	55	31
4:01- 5:00	25	20	27	44	62	75	69	73	55	62	55	29
5:01- 6:00	22	18	25	43	61	76	72	74	59	66	53	28

6:01- 7:00	26	21	24	44	61	74	70	74	59	59	51	32
7:01- 8:00	31	24	24	45	64	74	70	73	59	59	52	35
8:01- 9:00	31	26	24	44	65	72	69	74	60	58	49	40
9:01-10:00	32	29	29	47	63	70	67	71	59	55	50	42
10:01-11:00	36	33	35	48	64	69	66	69	59	60	56	45
11:01-12:00	45	38	43	51	62	68	66	68	66	63	60	48
12:01-13:00	38	36	40	52	62	67	66	69	64	61	59	48
13:01-14:00	39	34	39	53	65	69	67	70	65	60	58	48
14:01-15:00	43	35	36	54	63	69	67	70	68	61	60	50
15:01-16:00	37	39	39	58	67	70	70	72	71	64	63	47
16:01-17:00	38	43	41	62	70	70	72	74	73	67	66	46
17:01-18:00	45	49	44	67	75	70	75	76	75	68	74	43
18:01-19:00	37	45	45	63	73	68	75	74	69	67	70	40
19:01-20:00	35	44	48	60	74	68	74	71	66	70	68	38
20:01-21:00	34	43	51	57	74	68	71	69	64	68	65	36
21:01-22:00	34	40	48	57	73	68	70	69	64	66	65	33
22:01-23:00	32	38	45	57	72	68	69	68	63	64	66	32
23:01-24:00	39	35	43	57	70	68	66	69	62	62	65	29
Max Hour	18	18	21	18	18	6	18	18	18	20	18	15
Min Hour	6	6	7	6	6	13	1	23	4	10	9	6

- Monthly Calculated "undisturbed" Ground Temperatures** °C

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0.5 m	26.5	26.4	26.6	26.8	27.4	27.9	28.2	28.3	28.1	27.8	27.3	26.8
2.0 m	26.8	26.7	26.7	26.8	27.2	27.6	27.9	28.0	28.0	27.8	27.5	27.1
4.0 m	27.1	26.9	26.9	26.9	27.2	27.4	27.6	27.8	27.8	27.7	27.5	27.3

- **These ground temperatures should NOT BE USED in the GroundTemperatures object to compute building floor losses.
- The temperatures for 0.5 m depth can be used for GroundTemperatures:Surface.
- The temperatures for 4.0 m depth can be used for GroundTemperatures:Deep.
- Calculations use a standard soil diffusivity of 2.3225760E-03 {m**2/day}

- 6337 annual (wthr file) cooling degree-days (10°C baseline)
- 0 annual (wthr file) heating degree-days (10°C baseline)

- 3417 annual (wthr file) cooling degree-days (18°C baseline)
- 0 annual (wthr file) heating degree-days (18°C baseline)

- Climate type "Af" (Köppen classification)**
- Tropical wet (no dry season, rainforest, hot all year, lat. < 10°)
- Heating may not be required
- **Note that the Köppen classification shown here is derived algorithmically from the source weather data.
- It may not be indicative of the long term climate for this location.

Appendix E - Surface Heat Island Model - Typical Excel Based Input / Output Screen.

(Input values - green box - shown in Table 3.4)

FORCE-RESTORE MODEL FOR SURFACE TEMPERATURE PREDICTION
Urban Simulation
Notes: 4 reflections incorporated, symmetrical canyon, wall properties identical, each facet modelled

Surface Temperatures (deg C): Tf - Temperature of canyon floor, Tw - temperature of canyon wall, Td - deep temperature for indicated facet
Ldsky - incident longwave radiation from sky (W m^{-2}) - measured at top of canyon - may change with time

MODELLED EQUATIONS

$$\frac{dT}{dt} = \frac{2}{c} L^* - \Omega(T - Td)$$

Basic Equation

$$c = \mu \sqrt{\frac{2}{\Omega}}$$

$$\frac{dT_f}{dt} = \frac{2\varepsilon_f}{c}\left[\psi_{sf} L_s + \psi_{w_1 f}\varepsilon_{w_1}\sigma T_{w_1}^{\ 4} + \psi_{w_2 f}\varepsilon_{w_2}\sigma T_{w_2}^{\ 4} - \sigma T_f^{\ 4}\right] - \Omega(T_f - Td_f)$$

Temperature of the canyon floor

$$\frac{dT_{w_1}}{dt} = \frac{2\varepsilon_{w_1}}{c}\left[\psi_{sw_1} L_s + \psi_{w_1 w_2}\varepsilon_{w_2}\sigma T_{w_2}^{\ 4} + \psi_{fw_1}\varepsilon_f\sigma T_f^{\ 4} - \sigma T_{w_1}^{\ 4}\right] - \Omega(T_{w_1} - Td_{w_1})$$

Temperature of canyon wall #1

$$\frac{dT_{w_2}}{dt} = \frac{2\varepsilon_{w_2}}{c}\left[\psi_{sw_2} L_s + \psi_{w_1 w_2}\varepsilon_{w_1}\sigma T_{w_1}^{\ 4} + \psi_{fw_2}\varepsilon_f\sigma T_f^{\ 4} - \sigma T_{w_2}^{\ 4}\right] - \Omega(T_{w_2} - Td_{w_2})$$

Temperature of canyon wall #2

MODIFY CELLS WITH GREEN BORDER

Sfc Conditions		Initial Temperatures	
μ_f	1205	Tf	28.5
ε_f	0.95	Tdf	27.9
μ_w	2200	Tw1	35.5
ε_w	0.895	Tdw1	30.4
H/W	3	Tw2	38.2
Ldsky	415.33	Tdw2	30.4

(Hrs) from	Ldown (W m^{-2})
0	406.12
1	404.79
2	403.67
3	402.55
4	401.42
5	400.75
6	400.15
7	399.63
8	398.93
9	398.45
10	398.00

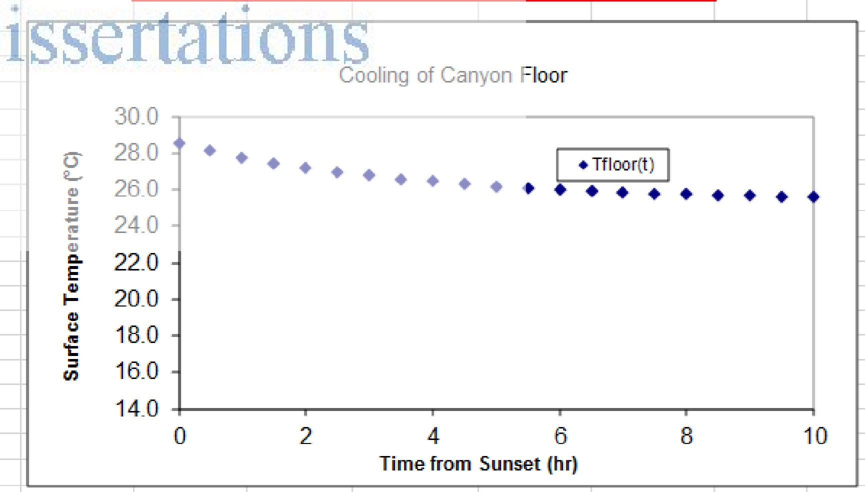
CONSTANTS	
dt	30
σ	5.67E-08
Ω	7.27E-05
Kelvin	273.15
VIEW FACTORS	
VFs	0.164398987
VFwf	0.417800506
VFww	0.832050294
VFfw	0.083974853
CALCULATED COEF	
cf	199864.1217
Cdf	13535870.9
cw	364897.1516
Cdw	24712793.34

HALF-HOURLY RESULTS

Time (Hrs) from Sunset	Tfloor(t)	Twall1(t)	Twall2(t)	L* floor(t)	L* wall1(t)	L* wall2(t)
0.00	28.50	35.50	38.20	31.86	-0.26	-27.77
0.50	28.90	34.86	37.01	-17.35	-42.88	-65.29
1.00	29.14	34.29	35.99	-22.66	-43.98	-61.65
1.50	29.27	33.78	35.13	-26.76	-44.78	-58.73
2.00	29.32	33.32	34.39	-29.92	-45.36	-56.39
2.50	29.31	32.91	33.77	-32.36	-45.78	-54.52
3.00	29.26	32.54	33.23	-34.25	-46.08	-53.00
3.50	29.18	32.22	32.76	-35.70	-46.28	-51.78
4.00	29.09	31.93	32.37	-36.83	-46.43	-50.79
4.50	28.99	31.68	32.03	-37.66	-46.51	-49.97
5.00	28.89	31.46	31.73	-38.30	-46.55	-49.31
5.50	28.80	31.26	31.48	-38.79	-46.57	-48.76
6.00	28.70	31.08	31.26	-39.16	-46.57	-48.32
6.50	28.61	30.93	31.07	-39.45	-46.56	-47.95
7.00	28.52	30.79	30.91	-39.67	-46.55	-47.65
7.50	28.44	30.68	30.76	-39.83	-46.53	-47.41
8.00	28.37	30.57	30.64	-39.96	-46.51	-47.21
8.50	28.30	30.48	30.53	-40.06	-46.48	-47.04
9.00	28.24	30.40	30.44	-40.13	-46.46	-46.90
9.50	28.19	30.33	30.36	-40.18	-46.43	-46.79
10.00	28.14	30.26	30.29	-40.22	-46.41	-46.70
			0.36			

DO NOT MODIFY CELLS WITH RED BORDER

Coefficients				
1.00E-05	68.280	2.12E-08	5.387E-08	
5.48E-06	34.877	4.22E-08	4.523E-09	5.075E-08
5.48E-06	34.877	4.22E-08	4.523E-09	5.075E-08



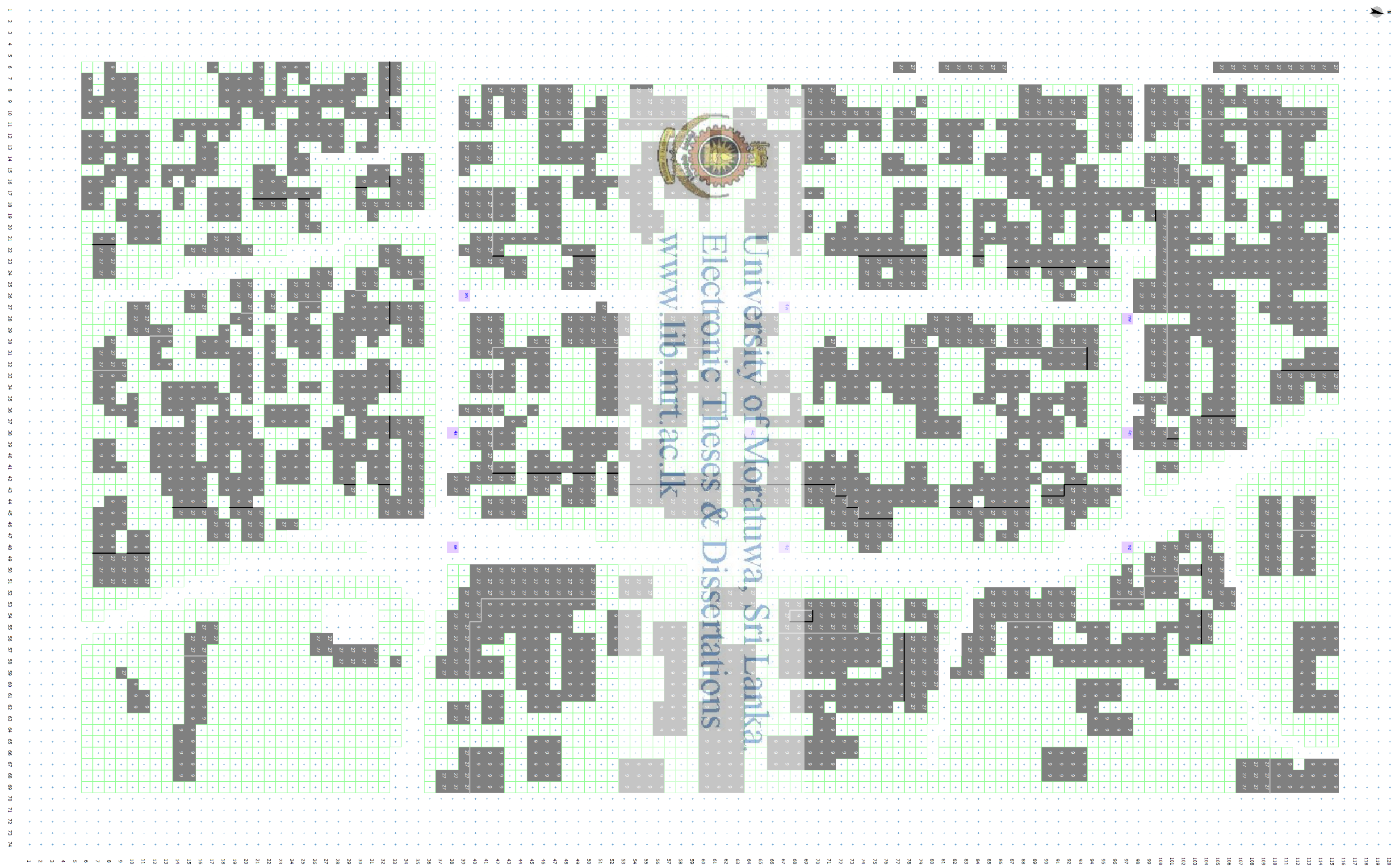
Time (s	Time (hrs)	k1	k2	k3	k4	Tf(t)	Tdf(t)	k1	k2	k3	k4	Tw1(t)	Tw1d(t)
0	0.00					301.65	301.05					308.65	303.55
30	0.01	8.25E-03	8.24E-03	8.24E-03	8.22E-03	301.66	301.05	-1.12E-02	-1.11E-02	-1.11E-02	-1.11E-02	308.6389	303.55
60	0.02	8.20E-03	8.18E-03	8.18E-03	8.16E-03	301.67	301.05	-1.11E-02	-1.11E-02	-1.11E-02	-1.11E-02	308.6277	303.55
90	0.03	8.14E-03	8.12E-03	8.12E-03	8.10E-03	301.67	301.05	-1.11E-02	-1.11E-02	-1.11E-02	-1.11E-02	308.6166	303.55
120	0.03	8.08E-03	8.06E-03	8.06E-03	8.05E-03	301.68	301.05	-1.11E-02	-1.11E-02	-1.11E-02	-1.11E-02	308.6055	303.55
150	0.04	8.02E-03	8.00E-03	8.00E-03	7.99E-03	301.69	301.05	-1.11E-02	-1.11E-02	-1.11E-02	-1.11E-02	308.5944	303.55
180	0.05	7.96E-03	7.95E-03	7.95E-03	7.93E-03	301.70	301.05	-1.11E-02	-1.11E-02	-1.11E-02	-1.10E-02	308.5834	303.55
210	0.06	7.91E-03	7.89E-03	7.89E-03	7.87E-03	301.71	301.05	-1.11E-02	-1.10E-02	-1.10E-02	-1.10E-02	308.5724	303.55
240	0.07	7.85E-03	7.83E-03	7.83E-03	7.82E-03	301.71	301.05	-1.10E-02	-1.10E-02	-1.10E-02	-1.10E-02	308.5613	303.55
270	0.08	7.79E-03	7.78E-03	7.78E-03	7.76E-03	301.72	301.05	-1.10E-02	-1.10E-02	-1.10E-02	-1.10E-02	308.5503	303.55
300	0.08	7.73E-03	7.72E-03	7.72E-03	7.70E-03	301.73	301.05	-1.10E-02	-1.10E-02	-1.10E-02	-1.10E-02	308.5394	303.55

Time (s	k1	k2	k3	k4	Tw2(t)	Tw2d(t)	Time	Interpolated Ldown	L* floor	L* wall 1	L* wall 2
0					311.35	303.55	0.00	406.12	31.9	-0.3	-27.8
30	-2.16E-02	-2.15E-02	-2.15E-02	-2.15E-02	311.3284565	303.55	0.01	406.1089	-10.6	-41.4	-69.8
60	-2.15E-02	-2.15E-02	-2.15E-02	-2.14E-02	311.3069724	303.55	0.02	406.0978	-10.7	-41.4	-69.7
90	-2.15E-02	-2.14E-02	-2.14E-02	-2.14E-02	311.2855476	303.55	0.03	406.0868	-10.9	-41.5	-69.6
120	-2.14E-02	-2.14E-02	-2.14E-02	-2.13E-02	311.2641818	303.55	0.03	406.0757	-11.0	-41.5	-69.5
150	-2.13E-02	-2.13E-02	-2.13E-02	-2.13E-02	311.2428748	303.55	0.04	406.0646	-11.1	-41.5	-69.4
180	-2.13E-02	-2.12E-02	-2.12E-02	-2.12E-02	311.2216266	303.55	0.05	406.0535	-11.3	-41.6	-69.4
210	-2.12E-02	-2.12E-02	-2.12E-02	-2.12E-02	311.2004368	303.55	0.06	406.0424	-11.4	-41.6	-69.3
240	-2.12E-02	-2.11E-02	-2.11E-02	-2.11E-02	311.1793054	303.55	0.07	406.0313	-11.5	-41.6	-69.2
270	-2.11E-02	-2.11E-02	-2.11E-02	-2.10E-02	311.1582322	303.55	0.08	406.0203	-11.6	-41.6	-69.1
300	-2.10E-02	-2.10E-02	-2.10E-02	-2.10E-02	311.137217	303.55	0.08	406.0092	-11.8	-41.7	-69.0

Appendix F - Site1 - Simplification and Modelling of context in ENVI-met. (representative model showing the High Edge - Green option)
(The receptor points are shown as numbered, purple cells)

Appendix F - Site2 - Simplification and Modelling of context in ENVI-met. (representative model showing the High Edge - Green option)
(The receptor points are shown as numbered, purple cells)

Appendix F - Site3 - Simplification and Modelling of context in ENVI-met. (representative model showing the High Edge - Green option)
(The receptor points are shown as numbered, purple cells)



Appendix F - Site4 - Simplification and Modelling of context in ENVI-met. (representative model showing the High Edge - Green option)
(The receptor points are shown as numbered, purple cells) (please note that the model is rotated for graphic representation - refer North point shown)

Appendix G – Detailed input data for ENVI-met simulation – name for simulation column, signifies individual models.

(the graph is a representation for all sites using site1 as an example) (abbreviations – g = green; gw = global warming; hc = high center; he = high edge; su = shadow umbrella)

		Main Data											Soil Data							Timing			TIMESTEPS						Building					PMV			NESTINGAREA			CLOUDS			TURBULENCE		
	Name for Simulation :	Firebase name for Output (Text):	Start Simulation at Day (DD.MM.YYYY):	Start Simulation at Time (HH:MM:SS):=	Total Simulation Time in Hours:	Save Model State each ? Min	Wind Speed in 10 m ab. Ground [m/s]=	Wind Direction (0:N..90:E..180:S..270:W..)	Roughness Length z0 at Reference Point=	Initial Temperature Atmosphere [K]=	Specific Humidity in 2500 m [g Water/kg air]:	Relative Humidity in 2m [%]:	Initial Temperature Upper Layer (0-20 cm) [K]=	Initial Temperature Middle Layer (20-50 cm) =	Initial Temperature Middle Layer (20-50 cm) [K]=	Initial Temperature Deep Layer (below 50 cm)[K]=	Relative Humidity Upper Layer (0-20 cm)=	Relative Humidity Middle Layer	Relative Humidity Deep Layer (below 50 cm)=	Update Surface Data each ? sec	Update Wind field each	Update Radiation and Shadows each	Update Plant Data each ?	Sun height for switching dt(0) -> dt(1) =	Sun height for switching dt(1) -> dt(2=	Time step (s) for interval 1 dt(0)=	Time step (s) for interval 2 dt(1)=	Time step (s) for interval 3 dt(2=	Inside Temperature [K]=	Heat Transmission Walls [W/m^2K] =1.94	Albedo Walls =0.6	[PMV]Settings for PMV-Calculation	Albedo Roofs	Walking Speed =	Energy-Exchange (Col. 2 M/A)=	Mech. Factor	Heat transfer resistance cloths	Use aver. solar input in nesting area (0:n,1:y)=	Include Nesting Grids in Output (0:n,1:y)=	Fraction of LOW clouds (x/8)=	Fraction of MEDIUM clouds (x/8)=	Fraction of HIGH clouds:	Turbulence Closure ABL (0:diagn., 1:prognos.)=	Turbulence Closure 3D Modell (0:diag.,1:prog)=	Upper Boundary for e-epsilon (0:clsd.,1:op.) =
1	S1	S1	14.04.2013	18:00:00	30	60	1.9	0	0.1	305.7	7	82	305.7	299.8	299.9	75	60	60	60	30	900	600	600	30	50	10	5	2	300	1.94	6	0.6	0.6	0.3	116	0	0.5	1	0	0	3	2	1	2	0
2	S1g	s1g	14.04.2014	18:00:00	30	60	1.9	0	0.1	305.7	7	82	305.7	299.8	299.9	75	60	60	60	30	900	600	600	30	50	10	5	2	300	1.94	6	0.6	0.6	0.3	116	0	0.5	1	0	0	3	2	1	2	0
3	s1ggw	s1ggw	14.04.2013	18:00:00	30	60	1.9	0	0.1	308.7	7	82	308.1	302.2	302.3	75	60	60	60	30	900	600	600	30	50	10	5	2	300	1.94	6	0.6	0.6	0.3	116	0	0.5	1	0	0	3	2	1	2	0
4	s1gw	s1gw	14.04.2013	18:00:00	30	60	1.9	0	0.1	308.7	7	82	308.1	302.2	302.3	75	60	60	60	30	900	600	600	30	50	10	5	2	300	1.94	6	0.6	0.6	0.3	116	0	0.5	1	0	0	3	2	1	2	0
5	s1hc	s1hc	14.04.2013	18:00:00	30	60	1.9	0	0.1	305.7	7	82	308.1	302.2	302.3	75	60	60	60	30	900	600	600	30	50	10	5	2	300	1.94	6	0.6	0.6	0.3	116	0	0.5	1	0	0	3	2	1	2	0
6	s1hcg	s1hc	14.04.2014	18:00:00	30	60	1.9	0	0.1	305.7	7	82	305.7	302.2	299.9	75	60	60	60	30	900	600	600	30	50	10	5	2	300	1.94	6	0.6	0.6	0.3	116	0	0.5	1	0	0	3	2	1	2	0
7	s1hcggw	s1hcggw	14.04.2014	18:00:00	30	60	1.9	0	0.1	305.7	7	82	305.7	302.2	299.9	75	60	60	60	30	900	600	600	30	50	10	5	2	300	1.94	6	0.6	0.6	0.3	116	0	0.5	1	0	0	3	2	1	2	0
8	s1he	s1he	14.04.2013	18:00:00	30	60	1.9	0	0.1	305.7	7	82	305.7	299.8	299.9	75	60	60	60	30	900	600	600	30	50	10	5	2	300	1.94	6	0.6	0.6	0.3	116	0	0.5	1	0	0	3	2	1	2	0
9	s1heg	s1heg	14.04.2013	18:00:00	30	60	1.9	0	0.1	305.7	7	82	305.7	302.2	302.3	75	60	60	60	30	900	600	600	30	50	10	5	2	300	1.94	6	0.6	0.6	0.3	116	0	0.5	1	0	0	3	2	1	2	0
10	s1heggw	s1heggw	14.04.2013	18:00:00	30	60	1.9	0	0.1	305.7	7	82	305.7	299.8	299.9	75	60	60	60	30	900	600	600	30	50	10	5	2	300	1.94	6	0.6	0.6	0.3	116	0	0.5	1	0	0	3	2	1	2	0
11	s1hegw	s1hegw	14.04.2013	18:00:00	30	60	1.9	0	0.1	305.7	7	82	305.7	299.8	299.9	75	60	60	60	30	900	600	600	30	50	10	5	2	300	1.94	6	0.6	0.6	0.3	116	0	0.5	1	0	0	3	2	1	2	0
12	s1hcgw	s1hcgw	14.04.2013	18:00:00	30	60	1.9	0	0.1	305.7	7	82	305.7	299.8	299.9	75	60	60	60	30	900	600	600	30	50	10	5	2	300	1.94	6	0.6	0.6	0.3	116	0	0.5	1	0	0	3	2	1	2	0
13	s1lcz2	s1lcz2	14.04.2013	18:00:00	30	60	1.9	0	0.1	305.7	7	82	305.7	299.8	299.9	75	60	60	60	30	900	600	600	30	50	10	5	2	300	1.94	6	0.6	0.6	0.3	116	0	0.5	1	0	0	3	2	1	2	0
14	s1lcz2g	s1lcz2g	14.04.2013	18:00:00	30	60	1.9	0	0.1	305.7	7	82	305.7	299.8	299.9	75	60	60	60	30	900	600	600	30	50	10	5	2	300	1.94	6	0.6	0.6	0.3	116	0	0.5	1	0	0	3	2	1	2	0
15	s1lcz2ggw	s1lcz2ggw	14.04.2013	18:00:00	30	60	1.9	0	0.1	305.7	7	82	308.1	302.2	302.3	75	60	60	60	30	900	600	600	30	50	10	5	2	300	1.94	6	0.6	0.6	0.3	116	0	0.5	1	0	0	3	2	1	2	0
16	s1lcz2gw	s1lcz2gw	14.04.2013	18:00:00	30	60	1.9	0	0.1	305.7	7	82	308.1	302.2	302.3	75	60	60	60	30	900	600	600	30	50	10	5	2	300	1.94	6	0.6	0.6	0.3	116	0	0.5	1	0	0	3	2	1	2	0
17	s1lcz3	s1lcz3	14.04.2013	18:00:00	30	60	1.9	0	0.1	305.7	7	82	305.7	299.8	299.9	75	60	60	60	30	900	600	600	30	50	10	5	2	300	1.94	6	0.6	0.6	0.3	116	0	0.5	1	0	0	3	2	1	2	0
18	s1lcz3g	s1lcz3g	14.04.2013	18:00:00	30	60	1.9	0	0.1	305.7	7	82	305.7	299.8	299.9	75	60	60	60	30	900	600	600	30	50	10	5	2	300	1.94	6	0.6	0.6	0.3	116	0	0.5	1	0	0	3	2	1	2	0
19	s1lcz3ggw	s1lcz3ggw	14.04.2013	18:00:00	30	60	1.9	0	0.1	305.7	7	82	308.1	302.2	302.3	75	60	60	60	30	900	600	600	30	50	10	5	2	300	1.94	6	0.6	0.6	0.3	116	0	0.5	1	0	0	3	2	1	2	0
20	s1lcz3gw	s1lcz3gw	14.04.2013	18:00:00	30	60	1.9	0	0.1	305.7	7	82	308.1	302.2	302.3	75	60	60	60	30	900	600	600	30	50	10	5	2	300	1.94	6	0.6	0.6	0.3	116	0	0.5	1	0	0	3	2	1	2	0
21	s1su	s1he	14.04.2013	18:00:00	30	60	1.9	0	0.1	305.7	7	82	305.7	299.8	299.9	75	60	60	60	30	900	600	600	30	50	10	5	2	300	1.94	6	0.6	0.6	0.3	116	0	0.5	1	0	0	3	2	1	2	0
22	s1sug	s1sug	14.04.2013	18:00:00	30	60	1.9	0	0.1	305.7	7	82	305.7	299.8	299.9	75	60	60	60	30	900	600	600	30	50	10	5	2	300	1.94	6	0.6	0.6	0.3	116	0	0.5	1	0	0	3	2	1	2	0
23	s1suggw	s1suggw	14.04.2013	18:00:00	30	60	1.9	0	0.1	305.7	7	82	308.1	302.2	302.3	75	60	60	60	30	900	600	600	30	50	10	5	2	300	1.94	6	0.6	0.6	0.3	116	0	0.5	1	0	0	3	2	1	2	0
24	s1sugw	s1sugw	14.04.2013	18:00:00	30	60	1.9	0	0.1	305.7	7	82	308.1	302.2	302.3	75	60	60	60	30	900	600	600	30	50	10	5	2	300	1.94	6	0.6	0.6	0.3	116	0	0.5	1	0	0	3	2	1	2	0

Appendix H - ENVI-met - Previous study areas – Detailed version of Table 11

Author/s - year	City	Climate zone (Köppen–Geiger climate classification system)	Parameter/s studied	Major finding
Validation and Simulation Software Combinations				
(Santo et al., 2012)	Lecce, Italy	Csa	Validation of ENVI-met / Air temperature	Conclusion - Although overall temperature trends are captured, ENVI-met shows some inertia in cooling during the night
(Francisco et al., 2012)	Belo Horizonte, Brazil	Aw	Validation of ENVI-met / Air temperature / Relative Humidity	ENVI-met validation; The outputs generated by numerical simulations were consistent with the available field observations in the study area
(Johansson et al., 2013)	São Paulo, Brazil	Cfa/Cwa	Temperature of Equivalent Perception (TEP) / Air Temperature / Wind speed / Relative Humidity / MRT	The microclimate of six different urban tissues were simulated on a typical summer day in São Paulo using a combination of the Meso-scale model BRAMS and the micro-scale model ENVI-met. Conclusions - • To combine model simulations of different scales may be a good strategy. • Although the TEP values are above the thermal comfort levels, shaded spaces tend to be much less stressful. • It is not only the amount of vegetation that is important but also the type of vegetation. • It is shown that the shade at ground level is better for high-rise than low-rise buildings, especially if the streets are oriented in a grid SW–NW and SE–NE. • Mutual shading by buildings is not enough due to the high solar angles in the tropics and street trees are needed to improve shade. • A higher amount of shading may have a negative impact on ventilation and low wind speed has an adverse effect on thermal comfort. • Shade is a more effective measure in lowering TEP than increasing the wind speed. • Create horizontal shade – either by vegetation as in this study or by other types of shading devices is probably an easier and more feasible strategy. • High buildings may lead to considerable reductions in MRT, and consequently, lower TEP (i.e. improved thermal comfort).
(C. Peng & Elwan, 2012)	Cairo, Egypt	BWh	Air Temperature / Wind speed / Relative Humidity / MRT / PMV	Developed experimental software and databased simulation workflow such that indoor environmental simulation of buildings in an urban neighbourhood can be grounded on outdoor environmental simulation of the neighbourhood. Simulation outputs from this outdoor-indoor coupling approach were brought together by a Web-based 3D virtual reality visualisation-modelling platform.
Vegetation				
(Srivanit & Hokao, 2013)	Saga, Japan	Cfa	Vegetation / Air temperature	Explored; adding trees to current green areas and by growing a grass layer on the rooftop of buildings. Hypothesized that the average maximum temperature would decrease and reach 2.27 °C in the peak of the summer (at 15:00) when the quantity of trees was increased by 20%. Conclusion - combining both modification methods led to the largest air temperature decrease with an average and maximum of 0.24 °C and 2.29 °C, respectively
(L. L. H. Peng & Jim, 2013)	Hong Kong	Cwa	Vegetation / PET	Conclusion - large-scale green-roof installation could bring neighbourhood-wide cooling, mitigate urban heat island effect, and furnish more comfortable thermal environment for urban residents
(Fröhlich & Matzarakis, 2012)	Freiburg, Germany	Cfb	Vegetation / SVF / PET	The study explored the effect of a redesigned area, reducing tree cover and introduction of impervious surfaces. Conclusion - Spatial distribution of heat stress shows strongest impact on heat stress by changes in shading, but also strong impact by changes on surface coverage
(Carfan & Galvani, 2012)	São Paulo, Brazil	Cfa / Cwa	PMV / MRT / Wind Speed	The model provided an overview of the urban climate and was used to point out problematical areas within the city (Sao Paulo) and thus seek solutions to minimize the entropic effects and improve the quality of life. Conclusion - analysis of thermal comfort index and the Wind flow showed the influence of high buildings in the local climatic environment
(Yang et al., 2011)	Shanghai, china	Cfa	PET	This article evaluated the effects of various urban design strategies on summertime outdoor thermal conditions, focusing on applications of high-albedo pavement and vegetation. Conclusions - • An increase of 0.4 in the ground surface albedo overall reduces the thermal comfort, as indicated by an increase of 5–7^{0}C in PET during the day with a marginal decrease of less than 1^{0}C at night. • Increasing greenery cover, especially tree cover, improves thermal comfort during the whole period under evaluation. • A reduction of up to 15^{0}C in daytime PET is achieved by adding a dense tree cover (LAI ¼ 6.4) over a grass lawn and up to 20^{0}C by adding the tree cover over the hard pavement with an albedo of 0.2
Wind				
(Yuan et al., 2012)	Beijing, China	Dwa	Wind Speed / PMV	Evaluation of the urban outdoor wind and thermal comfort is conducted based on the numerical modelling simulation Conclusions - • Strategies for Wind Comfort (1) Adjusting the function zoning to move the main pedestrians entertainment and relax flow lines away from poor ventilation areas. (2) To add additional plants (Trees with high stomatal resistance) in the areas with strong wind to reduce the wind speed. (3)Large canopy can be installed above the pedestrian areas for ameliorating the wind

				comfort at the pedestrian level. • Strategies for Thermal Comfort (1) Low permeability pavement is the most direct cause of the high air temperature at the pedestrian level, the applications of those surface types should be reduced. (2)The number of plants which have significant positive effects on thermal comfort should be increased.
(Fahmy & Sharples, 2008)	Cairo, Egypt	BWh	SVF / MRT / PMV	The study investigated the microclimatic thermal behaviour of hybrid traditional and modern street canyon types of urban form in Cairo in order to establish an urban planning tool for passive cooling Conclusions - • very dense urban layouts can have a beneficial impact upon outdoor thermal comfort • If incorrectly orientated, can severely reduce the potential for any wind- driven cooling because of excessive wind sheltering.
Urban Design / Morphology / Building Height				
(Carfan et al., 2012)	Ourinhos, São Paulo State, Brazil	Cfa / Cwa	Building height / Air Temperature	Analysed the effect of building height on the thermal comfort in Ourinhos Conclusion - The increase in the building height led to positive changes in the studied variables of local microclimate
(Middel et al., 2012)	Phoenix, Arizona, USA	BWh	LCZ / Air Temperature	The impact of urban form and landscaping was investigated exemplarily for two urban forms, i.e., Compact Low-rise and Open-set Low-rise. Conclusion - Results show that the effect of building arrangement and of function is a landscaping on cooling configuration. Analysis of near surface ambient temperatures from ENVI-met simulations relative to urban form and design reveals that increasing building density lowers air temperatures.
(Rosheidat et al., 2008)	Phoenix, Arizona, USA	BWh	air temperature / MRT / operative temperature / SET	Describes the use of the ENVI-met climate model to help in making decisions about the design of urban spaces with enhanced thermal comfort in Phoenix. The specific aim of the study is the simulation of the outdoor thermal conditions Conclusions - • the most effective strategy was shading • air movement, while decreasing the ambient temperature did little to decrease the MRT • water strategy had little effect as it was simulated only as a still water body with limited evaporation into the air • shaded high mass materials are preferable to low mass materials
(Emmanuel et al., 2007)	Colombo, Sri Lanka	Am	MRT / PET	Uses ENVI-met to simulate the effect of different urban design options on air and surface temperatures, as well as on outdoor thermal comfort. Conclusions - • The lowest daytime mean radiant temperatures result from high H/W ratios of streets. • the increase of H/W ratio from about 1 to 3 leads to a decrease in PET by about 10 °C. Differences in air and surface temperatures, as well as PET, are small during the night. • Strategies that lead to better air temperature mitigation may not necessarily lead to better thermal comfort. • shade enhancement through increased H/W ratios is clearly capable of significant reductions in PET • a critical urban design task in the humid tropics will be to guide the rapid urban growth towards efficient 'shade growth'
(Emmanuel & Fernando, 2007)	Colombo, Sri Lanka Phoenix, Arizona, USA	Am / BWh	MRT / Air temperature	The study examined the sensitivity of air temperature and mean radiant temperature (MRT) of built-up urban cores to urban-area geometry (the density of buildings), thermal properties of human-made surfaces (albedo) and green cover (street trees), in 2 warm-climate cities: Pettah, Colombo (Sri Lanka) and downtown Phoenix, Arizona (USA) Conclusions - • Although high albedo values lead to low daytime temperatures, the best thermal comfort, quantified by both the air temperature and MRT, was found in high-density development. • Density enhancement is a viable UHI mitigation option in built-up areas of warm climate cities. • Manipulation of thermal properties is an alternative strategy, but the practical utility of high albedo surfaces is questionable. Urban designers should use mitigation options that are based on human comfort, which is determined by both MRT and air temperature, rather than simply attempting to control air temperature alone.
(Ali-Toudert et al, 2007)	Ghardaia, Algeria	BWh	PET	The paper discusses the contribution of street design, i.e. aspect ratio (or height-to-width ratio, H/W) and solar orientation, towards the development of a comfortable microclimate at street level for pedestrians. Conclusions - • The results show contrasting patterns of thermal comfort between shallow and deep urban streets as well as between the various orientations studied. • A comparison of all case studies reveals that the time and period of day during which extreme heat stress occurs, as well as the spatial distribution of PETs at street level, depend strongly on aspect ratio and street orientation. • This is crucial since it will directly influence the design choices in relation to street usage, e.g. streets planned exclusively for pedestrian use or including motor traffic, and also the time of frequentation of urban spaces. • Both investigated urban factors can mitigate extreme heat stress if appropriately combined.
(Drach et al., 2012)	Glasgow, Scotland	Cfb	Air temperature	Explores the influence of urban morphology on local/micro-climate change in a pedestrianised street in Glasgow that is currently undergoing a process of rejuvenation. Conclusions - • The ability of urban morphology to interfere on the temperature and ventilation is notable. • Urban planning is an effective tool for designing and introducing protective niches on exterior spaces, promoting a positive impact on people's outdoor living experience. • In cold places, these actions may smooth the effects of increased (mostly unpleasant) ventilation.

Appendix I – Morphology / Physical Details of Receptor Point Data – Site1

(Generated manually using AutoCAD based LCZ map of Colombo. The percentages shown correspond to a 100m diameter influence area of Receptor Point)

Site / Model	receptor	Building surface fraction	Impervious surface fraction	Pervious surface fraction	Height of roughness elements	FAR	area of circle	3m	6m	9m	12m	15m	18m	21m	24m	27m	30m	33m	36m	impervious	pervious	building area	green	green surface fraction(for green case)
s1	c	42.9	7.6	49.5	6.2	2.6	7854.0	1719.4	701.0		950.0									598.7	3884.8	3370.4	3884.8	49.5
s1	n	40.9	10.0	49.1	10.6	4.3	7854.0	1154.0	951.1		461.0						643.9			786.5	3857.4	3210.1	3857.4	49.1
s1	e	29.1	29.0	41.9	8.9	2.6	7854.0	162.1	1566.8		81.7		400.0				74.8			2278.1	3290.3	2285.5	3290.3	41.9
s1	s	43.5	7.0	49.5	5.3	2.3	7854.0	1424.8	1580.2	170.3	241.5									551.2	3886.0	3416.8	3886.0	49.5
s1	w	21.1	40.8	38.1	11.1	2.3	7854.0		1310.3								350.0			3202.6	2991.1	1660.3	1597.5	20.3
s1	ne	29.9	31.6	38.5	13.3	4.0	7854.0	329.2	617.8	480.3			440.9				477.5			2481.3	3027.1	2345.6	3027.1	38.5
s1	se	35.0	33.1	31.9	8.2	2.9	7854.0	200.0	1947.5		100.0		502.5							2598.7	2505.3	2749.9	2505.3	31.9
s1	sw	20.7	21.7	57.6	7.8	1.6	7854.0	708.0	450.0	70.2			400.0							1701.1	4524.8	1628.1	2081.7	26.5
s1	nw	22.1	33.5	44.4	16.1	3.6	7854.0		688.9	273.2		123.2					649.6			2629.6	3489.4	1734.9	898.3	11.4
s1lcz3	c	42.9	7.6	49.5	9.0	3.9	7854.0	1719.4	701.0		950.0									598.7	3884.8	3370.4	3884.8	49.5
s1lcz3	n	40.9	10.0	49.1	9.0	3.7	7854.0	1154.0	951.1		461.0						643.9			786.5	3857.4	3210.1	3857.4	49.1
s1lcz3	e	29.1	29.0	41.9	9.0	2.6	7854.0	162.1	1566.8		81.7		400.0				74.8			2278.1	3290.3	2285.5	3290.3	41.9
s1lcz3	s	43.5	7.0	49.5	9.0	3.9	7854.0	1424.8	1580.2	170.3	241.5									551.2	3886.0	3416.8	3886.0	49.5
s1lcz3	w	21.1	40.8	38.1	9.0	1.9	7854.0		1310.3								350.0			3202.6	2991.1	1660.3	1597.5	20.3
s1lcz3	ne	29.9	31.6	38.5	9.0	2.7	7854.0	329.2	617.8	480.3			440.9				477.5			2481.3	3027.1	2345.6	3027.1	38.5
s1lcz3	se	35.0	33.1	31.9	9.0	3.2	7854.0	200.0	1947.5		100.0		502.5							2598.7	2505.3	2749.9	2505.3	31.9
s1lcz3	sw	20.7	21.7	57.6	9.0	1.9	7854.0	708.0	450.0	70.2			400.0							1701.1	4524.8	1628.1	2081.7	26.5
s1lcz3	nw	22.1	33.5	44.4	9.0	2.0	7854.0		688.9	273.2		123.2					649.6			2629.6	3489.4	1734.9	898.3	11.4
s1lcz2	c	42.9	7.6	49.5	27.0	11.6	7854.0	1719.4	701.0		950.0									598.7	3884.8	3370.4	3884.8	49.5
s1lcz2	n	40.9	10.0	49.1	27.0	11.0	7854.0	1154.0	951.1		461.0						643.9			786.5	3857.4	3210.1	3857.4	49.1
s1lcz2	e	29.1	29.0	41.9	27.0	7.9	7854.0	162.1	1566.8		81.7		400.0				74.8			2278.1	3290.3	2285.5	3290.3	41.9
s1lcz2	s	43.5	7.0	49.5	27.0	11.7	7854.0	1424.8	1580.2	170.3	241.5									551.2	3886.0	3416.8	3886.0	49.5
s1lcz2	w	21.1	40.8	38.1	27.0	5.7	7854.0		1310.3								350.0			3202.6	2991.1	1660.3	1597.5	20.3
s1lcz2	ne	29.9	31.6	38.5	27.0	8.1	7854.0	329.2	617.8	480.3			440.9				477.5			2481.3	3027.1	2345.6	3027.1	38.5
s1lcz2	se	35.0	33.1	31.9	27.0	9.5	7854.0	200.0	1947.5		100.0		502.5							2598.7	2505.3	2749.9	2505.3	31.9
s1lcz2	sw	20.7	21.7	57.6	27.0	5.6	7854.0	708.0	450.0	70.2			400.0							1701.1	4524.8	1628.1	2081.7	26.5
s1lcz2	nw	22.1	33.5	44.4	27.0	6.0	7854.0		688.9	273.2		123.2					649.6			2629.6	3489.4	1734.9	898.3	11.4
s1he	c	43.1	7.6	49.3	11.9	5.1	7854.0			2835.1						550.7				598.7	3869.5	3385.8	3869.5	49.3
s1he	n	41.4	10.0	48.6	15.9	6.6	7854.0			2011.9						1238.8				786.5	3816.8	3250.7	3816.8	48.6
s1he	e	29.1	29.0	41.9	22.4	6.5	7854.0			582.8						1700.3				2278.1	3292.8	2283.1	3292.8	41.9
s1he	s	43.3	7.0	49.7	15.2	6.6	7854.0			2223.1						1179.2				551.2	3900.4	3402.3	3900.4	49.7
s1he	w	23.6	40.8	35.6	19.9	4.7	7854.0			732.4						1123.3				3202.6	2795.7	1855.7	1597.5	20.3
s1he	ne	29.9	31.6	38.5	24.1	7.2	7854.0			378.1						1967.5				2481.3	3027.1	2345.6	3027.1	38.5
s1he	se	35.0	33.1	31.9	24.2	8.5	7854.0			422.3						2328.0				2598.7	2505.0	2750.2	2505.0	31.9
s1he	sw	20.9	21.7	57.5	23.2	4.8	7854.0			348.7						1290.3				1701.1	4514.0	1638.9	2081.7	26.5
s1he	nw	22.1	33.5	44.4	24.3	5.4	7854.0			259.6						1476.7				2629.6	3488.1	1736.2	898.3	11.4
s1hc	c	43.1	7.6	49.3	24.1	10.4	7854.0			550.7						2835.1				598.7	3869.5	3385.8	3869.5	49.3
s1hc	n	41.4	10.0	48.6	20.1	8.3	7854.0			1238.8						2011.9				786.5	3816.8	3250.7	3816.8	48.6
s1hc	e	29.1	29.0	41.9	13.6	4.0	7854.0			1700.3						582.8				2278.1	3292.8	2283.1	3292.8	41.9
s1hc	s	43.3	7.0	49.7	20.8	9.0	7854.0			1179.2						2223.1				551.2	3900.4	3402.3	3900.4	49.7
s1hc	w	23.6	40.8	35.6	16.1	3.8	7854.0			1123.3						732.4				3202.6	2795.7	1855.7	1597.5	20.3
s1hc	ne	29.9	31.6	38.5	11.9	3.6	7854.0			1967.5						378.1				2481.3	3027.1	2345.6	3027.1	38.5
s1hc	se	35.0	33.1	31.9	11.8	4.1	7854.0			2328.0						422.3				2598.7	2505.0	2750.2	2505.0	31.9
s1hc	sw	20.9	21.7	57.5	12.8	2.7	7854.0			1290.3						348.7				1701.1	4514.0	1638.9	2081.7	26.5
s1hc	nw	22.1	33.5	44.4	11.7	2.6	7854.0			1476.7						259.6				2629.6	3488.1	1736.2	898.3	11.4
s1su	c	42.6	7.6	49.8	15.0	6.4	7854.0	879.5		900.0					937.8	625.0				598.7	3912.9	3342.3	3912.9	49.8
s1su	n	42.1	10.0	47.9	15.2	6.4	7854.0	716.3		1135.9					462.5	987.9				786.5	3764.8	3302.7	3764.8	47.9
s1su	e	29.5	29.0	41.5	19.2	5.7	7854.0	428.4		291.4					856.6	744.0				2278.1	3255.5	2320.3	3255.5	41.5
s1su	s	43.4	7.0	49.6	14.9	6.4	7854.0	918.6		925.5					896.3	667.8				551.2	3894.6	3408.2	3894.6	49.6
s1su	w	23.6	40.8	35.6	6.5	1.5	7854.0	759.5		1096.3										3202.6	2795.5	1855.9	1597.5	20.3
s1su	ne	29.9	31.6	38.5	20.5	6.1	7854.0	199.1		443.9					808.1	897.4				2481.3	3024.2	2348.6	3024.2	38.5
s1su	se	35.0	33.1	31.9	16.4	5.7	7854.0	578.9		700.6					879.0	590.1				2598.7	2506.7	2748.6	2506.7	31.9
s1su	sw	20.9	21.7	57.5	6.2	1.3	7854.0	754.6		885.8										1701.1	4512.5	1640.4	2081.7	26.5
s1su	nw	22.1	33.5	44.4	7.2	1.6	7854.0	524.7		1211.6										2629.6	3488.1	1736.2	898.3	11.4

Appendix I – Morphology / Physical Details of Receptor Point Data – Site2

(Generated manually using AutoCAD based LCZ map of Colombo. The percentages shown correspond to a 100m diameter influence area of Receptor Point)

Site / model	Receptor	Building surface fraction	Impervious surface fraction	Pervious surface fraction	Height of roughness elements	Far	Area of circle	3m	6m	9m	12m	15m	18m	21m	24m	27m	30m	33m	36m	Impervious	Pervious	Building area	Green	Green surface fraction(for green case)
s2	c	44.6	4.0	51.3	8.0	3.6	7854.0	109.7	2454.8	62.3	520.3	136.9	221.9							316.5	4031.6	3505.9	4031.6	51.3
s2	n	53.2	9.5	37.3	11.2	6.0	7854.0		195.3	1311.1	2161.8	459.5	52.9							746.6	2926.8	4180.5	2926.8	37.3
s2	e	41.9	6.4	51.7	10.9	4.6	7854.0	1.5	2253.2	250.0	186.4						600.0			499.8	4063.1	3291.1	4063.1	51.7
s2	s	36.2	11.9	51.9	8.7	3.1	7854.0		1894.5	630.5					319.4					935.9	4073.7	2844.4	4073.7	51.9
s2	w	37.1	31.1	31.8	12.1	4.5	7854.0	300.0	1209.1		8.8	295.0	625.4		473.2					2443.4	2499.1	2911.4	2499.1	31.8
s2	ne	48.2	10.5	41.3	8.8	4.3	7854.0	411.2	983.9	1224.1	853.3	291.4					20.9			821.7	3247.6	3784.7	3247.6	41.3
s2	se	34.3	14.4	51.2	11.6	4.0	7854.0	300.0	1398.8	51.2			178.6		766.0					1134.4	4025.0	2694.6	4025.0	51.2
s2	sw	34.6	34.2	31.2	17.2	5.9	7854.0	19.9	435.2	617.8			897.9				744.1			2685.2	2453.8	2714.9	2453.8	31.2
s2	nw	42.3	31.4	26.3	11.2	4.7	7854.0		654.0	900.2	593.6	993.7	177.7							2466.9	2067.9	3319.2	2067.9	26.3
s2lcz3	c	44.6	4.0	51.3	9.0	4.0	7854.0			3505.9										316.5	4031.6	3505.9	4031.6	51.3
s2lcz3	n	53.2	9.5	37.3	9.0	4.8	7854.0			4180.6										746.6	2926.8	4180.6	2926.8	37.3
s2lcz3	e	41.9	6.4	51.7	9.0	3.8	7854.0			3291.1										499.8	4063.1	3291.1	4063.1	51.7
s2lcz3	s	36.2	11.9	51.9	9.0	3.3	7854.0			2844.4										935.9	4073.7	2844.4	4073.7	51.9
s2lcz3	w	37.1	31.1	31.8	9.0	3.3	7854.0			2911.4										2443.4	2499.1	2911.4	2499.1	31.8
s2lcz3	ne	48.2	10.5	41.3	9.0	4.3	7854.0			3784.7										821.7	3247.6	3784.7	3247.6	41.3
s2lcz3	se	34.3	14.4	51.2	9.0	3.1	7854.0			2694.6										1134.4	4025.0	2694.6	4025.0	51.2
s2lcz3	sw	34.6	34.2	31.2	9.0	3.1	7854.0			2714.9										2685.2	2453.8	2714.9	2453.8	31.2
s2lcz3	nw	42.3	31.4	26.3	9.0	3.8	7854.0			3319.2										2466.9	2067.9	3319.2	2067.9	26.3
s2lcz2	c	44.6	4.0	51.3	27.0	12.1	7854.0									3505.9				316.5	4031.6	3505.9	4031.6	51.3
s2lcz2	n	53.2	9.5	37.3	27.0	14.4	7854.0									4180.6				746.6	2926.8	4180.6	2926.8	37.3
s2lcz2	e	41.9	6.4	51.7	27.0	11.3	7854.0									3291.1				499.8	4063.1	3291.1	4063.1	51.7
s2lcz2	s	36.2	11.9	51.9	27.0	9.8	7854.0									2844.4				935.9	4073.7	2844.4	4073.7	51.9
s2lcz2	w	37.1	31.1	31.8	27.0	10.0	7854.0									2911.4				2443.4	2499.1	2911.4	2499.1	31.8
s2lcz2	ne	48.2	10.5	41.3	27.0	13.0	7854.0									3784.7				821.7	3247.6	3784.7	3247.6	41.3
s2lcz2	se	34.3	14.4	51.2	27.0	9.3	7854.0									2694.6				1134.4	4025.0	2694.6	4025.0	51.2
s2lcz2	sw	34.6	34.2	31.2	27.0	9.3	7854.0									2714.9				2685.2	2453.8	2714.9	2453.8	31.2
s2lcz2	nw	42.3	31.4	26.3	27.0	11.4	7854.0									3319.2				2466.9	2067.9	3319.2	2067.9	26.3
s2he	c	44.6	4.0	51.3	10.2	4.6	7854.0			3269.1						236.9				316.5	4031.6	3505.9	4031.6	51.3
s2he	n	53.4	9.5	37.1	17.9	9.5	7854.0			2128.5						2066.2				746.6	2912.7	4194.7	2912.7	37.1
s2he	e	41.9	6.4	51.8	16.2	6.8	7854.0			1975.1						1314.6				499.8	4064.4	3289.7	4064.4	51.8
s2he	s	37.0	11.9	51.1	16.6	6.1	7854.0			1682.4						1222.2				935.9	4013.5	2904.6	4013.5	51.1
s2he	w	37.1	31.1	31.8	19.8	7.4	7854.0			1156.8						1754.5				2443.4	2499.3	2911.3	2499.3	31.8
s2he	ne	48.2	10.5	41.3	18.6	9.0	7854.0			1771.1						2013.7				821.7	3247.4	3784.9	3247.4	41.3
s2he	se	34.3	14.4	51.3	17.0	5.8	7854.0			1499.5						1194.8				1134.4	4025.3	2694.3	4025.3	51.3
s2he	sw	35.3	34.2	30.5	23.1	8.2	7854.0			605.8						2169.7				2685.2	2393.2	2775.5	2393.2	30.5
s2he	nw	42.5	31.4	26.1	21.6	9.2	7854.0			994.1						2345.9				2466.9	2047.2	3340.0	2047.2	26.1
s2hc	c	44.6	4.0	51.3	25.8	11.5	7854.0			236.9						3269.1				316.5	4031.6	3505.9	4031.6	51.3
s2hc	n	53.4	9.5	37.1	18.1	9.7	7854.0			2066.2						2128.5				746.6	2912.7	4194.7	2912.7	37.1
s2hc	e	41.9	6.4	51.8	19.8	8.3	7854.0			1314.6						1975.1				499.8	4064.4	3289.7	4064.4	51.8
s2hc	s	37.0	11.9	51.1	19.4	7.2	7854.0			1222.2						1682.4				935.9	4013.5	2904.6	4013.5	51.1
s2hc	w	37.1	31.1	31.8	16.2	6.0	7854.0			1754.5						1156.8				2443.4	2499.3	2911.3	2499.3	31.8
s2hc	ne	48.2	10.5	41.3	17.4	8.4	7854.0			2013.7						1771.1				821.7	3247.4	3784.9	3247.4	41.3
s2hc	se	34.3	14.4	51.3	19.0	6.5	7854.0			1194.8						1499.5				1134.4	4025.3	2694.3	4025.3	51.3
s2hc	sw	35.3	34.2	30.5	12.9	4.6	7854.0			2169.7						605.8				2685.2	2393.2	2775.5	2393.2	30.5
s2hc	nw	42.5	31.4	26.1	14.4	6.1	7854.0			2345.9						994.1				2466.9	2047.2	3340.0	2047.2	26.1
s2su	c	44.7	4.0	51.3	18.0	8.0	7854.0	667.2		692.3					1017.2	1130.9				316.5	4029.9	3507.5	4029.9	51.3
s2su	n	53.3	9.5	37.2	17.1	9.1	7854.0	693.9		1243.0					757.8	1492.7				746.6	2920.0	4187.3	2920.0	37.2
s2su	e	41.9	6.4	51.8	20.6	8.6	7854.0	683.8		1.5					1492.5	1111.9				499.8	4064.4	3289.7	4064.4	51.8
s2su	s	37.0	11.9	51.1	13.6	5.0	7854.0	641.7		1121.7					1088.2	52.9				935.9	4013.5	2904.6	4013.5	51.1
s2su	w	37.1	31.1	31.8	16.1	6.0	7854.0	600.4		819.4					868.3	623.2				2443.4	2499.3	2911.3	2499.3	31.8
s2su	ne	48.2	10.5	41.4	21.4	10.3	7854.0	20.9		1015.2					785.4	1960.3				821.7	3250.5	3781.8	3250.5	41.4
s2su	se	34.3	14.4	51.3	23.0	7.9	7854.0	225.0		102.9					1171.1	1195.2				1134.4	4025.3	2694.3	4025.3	51.3
s2su	sw	33.4	34.2	32.4	10.6	3.5	7854.0	1449.6		392.8					419.4	364.4				2685.2	2542.5	2626.2	2542.5	32.4
s2su	nw	42.5	31.4	26.1	12.6	5.4	7854.0	894.4		1352.3					772.5	320.7				2466.9	2047.2	3340.0	2047.2	26.1

Appendix I – Morphology / Physical Details of Receptor Point Data – Site3

(Generated manually using AutoCAD based LCZ map of Colombo. The percentages shown correspond to a 100m diameter influence area of Receptor Point)

Site	Receptor	Building surface fraction	Impervious surface fraction	Pervious surface fraction	Height of roughness elements	Far	Area of circle	3m	6m	9m	12m	15m	18m	21m	24m	27m	30m	33m	36m	Impervious	Pervious	Building area	Green	Green surface fraction(for green case)
S3	C	59.98	5.89	34.13	6.00	3.60	7853.98	973.55	2851.79	793.49	92.02									462.40	2680.74	4710.84	2680.7	34.1
S3	N	49.32	13.06	37.61	5.86	2.89	7853.98	1395.57	1549.23	692.88	183.20	53.04								1025.84	2954.21	3873.93	2954.2	37.6
S3	E	40.00	12.70	47.31	4.63	1.85	7853.98	1591.15	1472.79		77.49									997.07	3715.47	3141.43	3715.5	47.3
S3	S	39.08	21.43	39.49	8.29	3.24	7853.98	1135.79		788.08	745.77	399.57								1683.01	3101.76	3069.21	3101.8	39.5
S3	W	44.49	19.71	35.80	13.83	6.15	7853.98	410.32	1195.27	474.57	375.00						1038.84			1547.89	2812.09	3494.00	2812.1	35.8
S3	Ne	49.71	16.43	33.86	5.73	2.85	7853.98	1388.16	1684.25	632.02	200.00									1290.55	2658.99	3904.44	2659.0	33.9
S3	Se	38.58	19.51	41.91	8.71	3.36	7853.98	258.20	2142.76	8.81	183.20				436.87					1532.48	3291.65	3029.85	3291.7	41.9
S3	Sw	41.87	30.52	27.61	8.72	3.65	7853.98	599.17	1293.45	503.54		492.36	400.00							2396.68	2168.79	3288.52	2168.8	27.6
S3	Nw	37.14	26.64	36.22	12.03	4.47	7853.98	755.81	764.38	178.54			435.84		782.02					2092.63	2844.76	2916.60	2844.8	36.2
S3lcz3	C	59.97	5.89	34.14	9.00	5.40	7853.98			4710.00										462.40	2681.59	4710.00	2681.6	34.1
S3lcz3	N	49.32	13.06	37.61	9.00	4.44	7853.98			3873.93										1025.84	2954.21	3873.93	2954.2	37.6
S3lcz3	E	40.00	12.70	47.31	9.00	3.60	7853.98			3141.43										997.07	3715.48	3141.43	3715.5	47.3
S3lcz3	S	39.08	21.43	39.49	9.00	3.52	7853.98			3069.21										1683.01	3101.77	3069.21	3101.8	39.5
S3lcz3	W	44.49	19.71	35.80	9.00	4.00	7853.98			3494.00										1547.89	2812.09	3494.00	2812.1	35.8
S3lcz3	Ne	49.71	16.43	33.86	9.00	4.47	7853.98			3904.44										1290.55	2658.99	3904.44	2659.0	33.9
S3lcz3	Se	38.58	19.51	41.91	9.00	3.47	7853.98			3029.85										1532.48	3291.65	3029.85	3291.7	41.9
S3lcz3	Sw	41.87	30.52	27.61	9.00	3.77	7853.98			3288.52										2396.68	2168.78	3288.52	2168.8	27.6
S3lcz3	Nw	37.14	26.64	36.22	9.00	3.34	7853.98			2916.60										2092.63	2844.76	2916.60	2844.8	36.2
S3lcz2	C	59.97	5.89	34.14	27.00	16.19	7853.98									4710.00				462.40	2681.59	4710.00	2681.6	34.1
S3lcz2	N	49.32	13.06	37.61	27.00	13.32	7853.98									3873.93				1025.84	2954.21	3873.93	2954.2	37.6
S3lcz2	E	40.00	12.70	47.31	27.00	10.80	7853.98									3141.43				997.07	3715.48	3141.43	3715.5	47.3
S3lcz2	S	39.08	21.43	39.49	27.00	10.55	7853.98									3069.21				1683.01	3101.77	3069.21	3101.8	39.5
S3lcz2	W	44.49	19.71	35.80	27.00	12.01	7853.98									3494.00				1547.89	2812.09	3494.00	2812.1	35.8
S3lcz2	Ne	49.71	16.43	33.86	27.00	13.42	7853.98									3904.44				1290.55	2658.99	3904.44	2659.0	33.9
S3lcz2	Se	38.58	19.51	41.91	27.00	10.42	7853.98									3029.85				1532.48	3291.65	3029.85	3291.7	41.9
S3lcz2	Sw	41.87	30.52	27.61	27.00	11.31	7853.98									3288.52				2396.68	2168.78	3288.52	2168.8	27.6
S3lcz2	Nw	37.14	26.64	36.22	27.00	10.03	7853.98									2916.60				2092.63	2844.76	2916.60	2844.8	36.2
S3he	C	59.94	5.89	34.17	9.00	5.39	7853.98			4707.89										462.40	2683.69	4707.89	2683.7	34.2
S3he	N	49.32	13.06	37.62	18.01	8.88	7853.98			1934.37						1939.41				1025.84	2954.35	3873.78	2954.4	37.6
S3he	E	39.90	12.70	47.40	16.45	6.57	7853.98			1836.31						1297.61				997.07	3722.99	3133.92	3723.0	47.4
S3he	S	42.34	21.43	36.23	19.95	8.45	7853.98			1301.90						2023.68				1683.01	2845.40	3325.57	2845.4	36.2
S3he	W	44.47	19.71	35.83	18.54	8.24	7853.98			1641.78						1850.60				1547.89	2813.71	3492.38	2813.7	35.8
S3he	Ne	50.22	16.43	33.35	20.40	10.24	7853.98			1446.49						2497.61				1290.55	2619.32	3944.11	2619.3	33.4
S3he	Se	38.50	19.51	41.98	19.49	7.50	7853.98			1261.88						1762.22				1532.48	3297.40	3024.10	3297.4	42.0
S3he	Sw	41.80	30.52	27.69	21.08	8.81	7853.98			1079.43						2203.48				2396.68	2174.39	3282.91	2174.4	27.7
S3he	Nw	37.15	26.64	36.20	24.40	9.06	7853.98			422.12						2495.81				2092.63	2843.42	2917.93	2843.4	36.2
S3hc	C	59.94	5.89	34.17	27.00	16.18	7853.98									4707.89				462.40	2683.69	4707.89	2683.7	34.2
S3hc	N	49.32	13.06	37.62	17.99	8.87	7853.98			1939.41						1934.37				1025.84	2954.35	3873.78	2954.4	37.6
S3hc	E	39.90	12.70	47.40	19.55	7.80	7853.98			1297.61						1836.31				997.07	3722.99	3133.92	3723.0	47.4
S3hc	S	42.34	21.43	36.23	16.05	6.79	7853.98			2023.68						1301.90				1683.01	2845.40	3325.57	2845.4	36.2
S3hc	W	44.47	19.71	35.83	17.46	7.76	7853.98			1850.60						1641.78				1547.89	2813.71	3492.38	2813.7	35.8
S3hc	Ne	50.22	16.43	33.35	15.60	7.83	7853.98			2497.61						1446.49				1290.55	2619.32	3944.11	2619.3	33.4
S3hc	Se	38.50	19.51	41.98	16.51	6.36	7853.98			1762.22						1261.88				1532.48	3297.40	3024.10	3297.4	42.0
S3hc	Sw	41.80	30.52	27.69	14.92	6.24	7853.98			2203.48						1079.43				2396.68	2174.39	3282.91	2174.4	27.7
S3hc	Nw	37.15	26.64	36.20	11.60	4.31	7853.98			2495.81						422.12				2092.63	2843.42	2917.93	2843.4	36.2
S3su	C	59.98	5.89	34.13	16.58	9.95	7853.98	926.23		1346.63					867.02	1571.11				462.40	2680.60	4710.99	2680.6	34.1
S3su	N	49.34	13.06	37.60	16.04	7.92	7853.98	877.17		1050.02					836.89	1111.32				1025.84	2952.74	3875.40	2952.7	37.6
S3su	E	39.95	12.70	47.36	16.30	6.51	7853.98	1272.58							1010.64	854.37				997.07	3719.32	3137.59	3719.3	47.4
S3su	S	42.36	21.43	36.21	17.25	7.31	7853.98	618.13		831.87					882.07	995.11				1683.01	2843.78	3327.19	2843.8	36.2
S3su	W	44.49	19.71	35.80	14.20	6.32	7853.98	799.25		1297.27					732.47	665.44				1547.89	2811.66	3494.43	2811.7	35.8
S3su	Ne	50.25	16.43	33.32	17.93	9.01	7853.98	1005.94		444.19					1222.84	1273.33				1290.55	2617.13	3946.30	2617.1	33.3
S3su	Se	38.36	19.51	42.13	10.80	4.14	7853.98	602.49		1808.64					601.83					1532.48	3308.54	3012.96	3308.5	42.1
S3su	Sw	41.87	30.52	27.62	10.45	4.38	7853.98	1316.22		1179.98					527.51	264.66				2396.68	2168.93	3288.37	2168.9	27.6
S3su	Nw	37.13	26.64	36.22	14.24	5.29	7853.98	746.17		969.51					615.41	585.22				2092.63	2845.04	2916.31	2845.0	36.2

Appendix I – Morphology / Physical Details of Receptor Point Data – Site4

(Generated manually using AutoCAD based LCZ map of Colombo. The percentages shown correspond to a 100m diameter influence area of Receptor Point)

site	receptor	Building surface fraction	Impervious surface fraction	Pervious surface fraction	Height of roughness elements	FAR	area of circle	3m	6m	9m	12m	15m	18m	21m	24m	27m	30m	33m	36m	impervious	pervious	building area	green	green surface fraction(for green case)
s4	c	47.6	0.7	51.7	5.7	2.7	7854.0	2718.1	722.8								297.8			52.3	4063.1	3738.6	4063.1	51.7
s4	n	42.9	22.7	34.4	4.5	1.9	7854.0	2194.9	897.3	155.7		123.5								1780.0	2702.5	3371.5	2702.5	34.4
s4	e	41.0	17.1	41.9	16.2	6.7	7854.0	865.4	699.7	87.3						752.1	812.3			1342.9	3294.4	3216.7	3294.4	41.9
s4	s	43.9	17.9	38.3	6.5	2.8	7854.0	1240.6	1218.8	169.7	815.9									1402.6	3006.4	3445.0	3006.4	38.3
s4	w	34.6	12.7	52.7	4.3	1.5	7854.0	1545.2	1174.7											997.1	4137.0	2719.9	4137.0	52.7
s4	ne	37.9	26.2	35.9	6.5	2.5	7854.0	745.9	990.9	1239.7										2055.2	2822.3	2976.5	2822.3	35.9
s4	se	35.3	37.0	27.8	6.4	2.2	7854.0	602.8	1698.8		467.4									2902.9	2182.1	2768.9	2182.1	27.8
s4	sw	37.7	22.0	40.4	5.4	2.0	7854.0	855.4	1919.3	82.6	100.0									1726.6	3170.0	2957.3	3170.0	40.4
s4	nw	54.1	12.2	33.7	3.7	2.0	7854.0	3300.8	918.4	32.3										955.9	2646.6	4251.5	2646.6	33.7
s4lcz3	c	47.6	0.7	51.7	9.0	4.3	7854.0			3738.6										52.3	4063.1	3738.6	4063.1	51.7
s4lcz3	n	42.9	22.7	34.4	9.0	3.9	7854.0			3371.5										1780.0	2702.5	3371.5	2702.5	34.4
s4lcz3	e	41.0	17.1	41.9	9.0	3.7	7854.0			3216.7										1342.9	3294.4	3216.7	3294.4	41.9
s4lcz3	s	43.9	17.9	38.3	9.0	3.9	7854.0			3445.0										1402.6	3006.4	3445.0	3006.4	38.3
s4lcz3	w	34.6	12.7	52.7	9.0	3.1	7854.0			2719.9										997.1	4137.0	2719.9	4137.0	52.7
s4lcz3	ne	37.9	26.2	35.9	9.0	3.4	7854.0			2976.5										2055.2	2822.3	2976.5	2822.3	35.9
s4lcz3	se	35.3	37.0	27.8	9.0	3.2	7854.0			2768.9										2902.9	2182.1	2768.9	2182.1	27.8
s4lcz3	sw	37.7	22.0	40.4	9.0	3.4	7854.0			2957.3										1726.6	3170.0	2957.3	3170.0	40.4
s4lcz3	nw	54.1	12.2	33.7	9.0	4.9	7854.0			4251.5										955.9	2646.6	4251.5	2646.6	33.7
s4lcz2	c	47.6	0.7	51.7	27.0	12.9	7854.0									3738.6				52.3	4063.1	3738.6	4063.1	51.7
s4lcz2	n	42.9	22.7	34.4	27.0	11.6	7854.0									3371.5				1780.0	2702.5	3371.5	2702.5	34.4
s4lcz2	e	41.0	17.1	41.9	27.0	11.1	7854.0									3216.7				1342.9	3294.4	3216.7	3294.4	41.9
s4lcz2	s	43.9	17.9	38.3	27.0	11.8	7854.0									3445.0				1402.6	3006.4	3445.0	3006.4	38.3
s4lcz2	w	34.6	12.7	52.7	27.0	9.4	7854.0									2719.9				997.1	4137.0	2719.9	4137.0	52.7
s4lcz2	ne	37.9	26.2	35.9	27.0	10.2	7854.0									2976.5				2055.2	2822.3	2976.5	2822.3	35.9
s4lcz2	se	35.3	37.0	27.8	27.0	9.5	7854.0									2768.9				2902.9	2182.1	2768.9	2182.1	27.8
s4lcz2	sw	37.7	22.0	40.4	27.0	10.2	7854.0									2957.3				1726.6	3170.0	2957.3	3170.0	40.4
s4lcz2	nw	54.1	12.2	33.7	27.0	14.6	7854.0									4251.5				955.9	2646.6	4251.5	2646.6	33.7
s4he	c	47.6	0.7	51.7	14.1	6.7	7854.0			2688.7						1048.7				52.3	4064.3	3737.4	4064.3	51.7
s4he	n	42.9	22.7	34.5	17.8	7.6	7854.0			1711.3						1654.5				1780.0	2708.2	3365.9	2708.2	34.5
s4he	e	41.0	17.1	41.9	19.0	7.8	7854.0			1433.2						1783.2				1342.9	3294.7	3216.4	3294.7	41.9
s4he	s	43.9	17.9	38.3	18.6	8.2	7854.0			1607.9						1837.5				1402.6	3006.0	3445.4	3006.0	38.3
s4he	w	34.6	12.7	52.7	13.3	4.6	7854.0			2069.8						644.7				997.1	4142.5	2714.4	4142.5	52.7
s4he	ne	37.9	26.2	35.9	19.9	7.5	7854.0			1177.4						1798.8				2055.2	2822.6	2976.2	2822.6	35.9
s4he	se	35.3	37.0	27.8	22.2	7.8	7854.0			742.7						2026.1				2902.9	2182.3	2768.8	2182.3	27.8
s4he	sw	37.7	22.0	40.4	20.1	7.6	7854.0			1136.5						1820.7				1726.6	3170.1	2957.2	3170.1	40.4
s4he	nw	54.2	12.2	33.6	15.0	8.2	7854.0			2826.1						1429.3				955.9	2642.7	4255.4	2642.7	33.6
s4hc	c	47.6	0.7	51.7	21.9	10.4	7854.0			1048.7						2688.7				52.3	4064.3	3737.4	4064.3	51.7
s4hc	n	42.9	22.7	34.5	18.2	7.8	7854.0			1654.5						1711.3				1780.0	2708.2	3365.9	2708.2	34.5
s4hc	e	41.0	17.1	41.9	17.0	7.0	7854.0			1783.2						1433.2				1342.9	3294.7	3216.4	3294.7	41.9
s4hc	s	43.9	17.9	38.3	17.4	7.6	7854.0			1837.5						1607.9				1402.6	3006.0	3445.4	3006.0	38.3
s4hc	w	34.6	12.7	52.7	22.7	7.9	7854.0			644.7						2069.8				997.1	4142.5	2714.4	4142.5	52.7
s4hc	ne	37.9	26.2	35.9	16.1	6.1	7854.0			1798.8						1177.4				2055.2	2822.6	2976.2	2822.6	35.9
s4hc	se	35.3	37.0	27.8	13.8	4.9	7854.0			2026.1						742.7				2902.9	2182.3	2768.8	2182.3	27.8
s4hc	sw	37.7	22.0	40.4	15.9	6.0	7854.0			1820.7						1136.5				1726.6	3170.1	2957.2	3170.1	40.4
s4hc	nw	54.2	12.2	33.6	21.0	11.4	7854.0			1429.3						2826.1				955.9	2642.7	4255.4	2642.7	33.6
s4su	c	47.6	0.7	51.7	15.1	7.2	7854.0	1310.3		524.4					1206.4	697.8				52.3	4062.8	3738.9	4062.8	51.7
s4su	n	42.9	22.7	34.4	20.6	8.9	7854.0			931.5					1575.4	864.7				1780.0	2702.4	3371.6	2702.4	34.4
s4su	e	41.0	17.1	41.9	19.6	8.0	7854.0	103.0		1072.9					708.5	1332.0				1342.9	3294.7	3216.4	3294.7	41.9
s4su	s	43.9	17.9	38.3	18.8	8.2	7854.0	777.5		362.7					1040.5	1264.5				1402.6	3006.3	3445.1	3006.3	38.3
s4su	w	38.7	12.7	48.6	12.4	4.8	7854.0	1035.7		1035.7					268.0	698.7				997.1	3818.7	3038.2	3818.7	48.6
s4su	ne	37.9	26.2	35.9	13.8	5.2	7854.0	420.2		1602.4					160.8	793.0				2055.2	2822.3	2976.5	2822.3	35.9
s4su	se	35.3	37.0	27.8	13.3	4.7	7854.0	1487.5							706.7	574.7				2902.9	2182.1	2768.9	2182.1	27.8
s4su	sw	37.7	22.0	40.4	12.7	4.8	7854.0	885.1		997.2					992.4	82.9				1726.6	3169.7	2957.6	3169.7	40.4
s4su	nw	54.1	12.2	33.7	19.4	10.5	7854.0	372.1		950.7					2033.8	895.1				955.9	2646.4	4251.7	2646.4	33.7