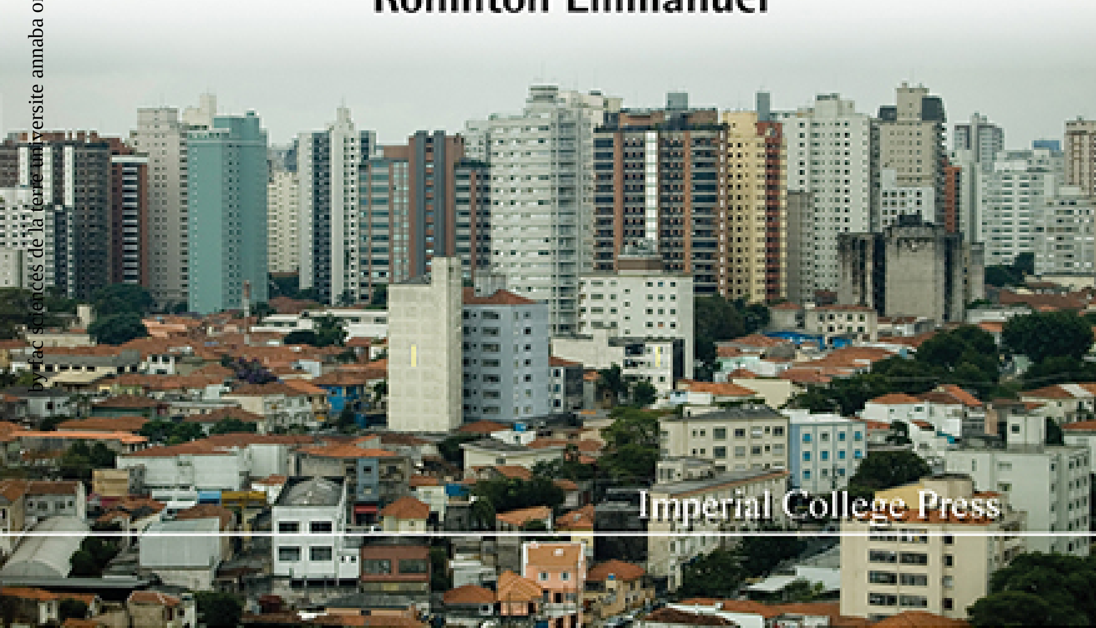
URBAN CLIMATE CHALLENGES IN THE TROPICS

Rethinking Planning and Design Opportunities

Editor
Rohinton Emmanuel



URBAN CLIMATE CHALLENGES IN THE TROPICS

Rethinking Planning and Design Opportunities

This page intentionally left blank

URBAN CLIMATE CHALLENGES IN THE TROPICS

Rethinking Planning and Design Opportunities

Editor

Rohinton Emmanuel

Glasgow Caledonian University, UK

ICP

Imperial College Press

Published by

Imperial College Press
57 Shelton Street
Covent Garden
London WC2H 9HE

Distributed by

World Scientific Publishing Co. Pte. Ltd.
5 Toh Tuck Link, Singapore 596224
USA office: 27 Warren Street, Suite 401-402, Hackensack, NJ 07601
UK office: 57 Shelton Street, Covent Garden, London WC2H 9HE

Library of Congress Cataloging-in-Publication Data
Names: Emmanuel, M. Rohinton, 1962– editor.
Title: Urban climate challenges in the tropics : rethinking planning and design opportunities / [edited by] Rohinton Emmanuel (School of Engineering and the Built Environment, Glasgow Caledonian University, UK).
Description: New Jersesy : Imperial College Press, 2016. | Includes bibliographical references and index.
Identifiers: LCCN 2015035206 | ISBN 9781783268405 (alk. paper)
Subjects: LCSH: City planning--Climatic factors--Tropics. | Urban climatology--Tropics.
Classification: LCC TD168.5 .U73 2016 | DDC 711--dc23
LC record available at http://lccn.loc.gov/2015035206

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

In-house Editors: Mary Simpson/Nisha Rahul

Typeset by Stallion Press
Email: enquiries@stallionpress.com

Printed in Singapore

"The acquisition of more knowledge about the climate of cities may in the long run be one of the keys to man's survival."

(Lowry, 1967: 24)

"Urban climate management is a classic instance of municipalism in action: it depends upon local capacity, competences and political autonomy."

(Hebbert and Jankovic, 2013: 1345)

This page intentionally left blank

Acknowledgments

The sparsely researched but increasingly important area of climate sensitive tropical urban design is beginning to receive its long overdue attention and this collection is our attempt to place the current thinking on record. It wouldn't have seen the light of day without the kind assistance of so many individuals who deserve special mention.

My foremost thanks to *Prof Michael Hebbert*, University College London Bartlett School of Planning and Editor, Planning Perspectives, for promoting the idea of this book to the Publishers. *Dr Jane Sayers*, Commissioning Editor for Imperial College Press (ICP) ably guided the initial proposal from the review process through to the contract stage and I am very thankful to her enthusiasm for the subject matter and the need for a book such as this. Thanks also to *Thomas Stottor* and *Tasha D'Cruz* of ICP for all their assistance in seeing the final work to print.

The acknowledgment will not be complete without mention of the kind permission to reproduce images used herein by chapter authors. Chapter authors join me in expressing their gratitude to the following copyright holders for their kind assistance:

Chapter 1: Prof Detlef van Vuuren (Figs. 1.1 and 1.3); **Chapter 2**: Prof Eduardo Kruger (Fig. 2.2), Dr Harimi Djamila (Fig. 2.3), Dr R.-L. Hwang (Fig. 2.4); **Chapter 4**: Dr Adam Goliger (Fig. 4.6); **Chapter 5**: Júlio César Calsinski (Fig. 5.2), Luciana Schwandner Ferreira (Figs. 5.1a, 5.4–5.7 and 5.15), Bruno Mendes (Fig. 5.13), Eduardo Pizzaro (Figs. 5.1b–5.1f and 5.15), Dr Paula Shinzato (Figs. 5.8–5.10); **Chapter 7**: Dr Iain Stewart (Figs. 7.1–7.5), Drs G. Kaveckis and B. Bechtel (Fig. 7.6), Japan International Cooperation Agency (Fig. 7.7), Ms Dilmini Dissanayake and Mr Gihan Muthugala (Fig. 7.11); **Chapter 8**: Victoria Gana, Enosh Subramanium and Dimple Shah (preparation of all images and tables); **Chapter 9**: Eduardo A. Roxo Pereira (Figs. 9.1a, 9.1b, 9.2a and 9.2b), Gisele Barbosa — (Figs. 9.3a, 9.3b and 9.3c), Rafael RamilosF Braga (Fig. 9.6), Dr Henrique Drach (Figs. 9.9a and 9.9b), Roberto Ghione (Figs. 9.11a, 9.11b and 9.11c), Municipalidad de Buenos Aires — Historia de los Barrios (Figs. 9.12a and 9.12b), CDURP — Rio de Janeiro port region urban development company (Figs. 9.13a and 9.13b), Nelson Kon (Figs. 9.14a, 9.14b, 9.19a, 9.20c, 9.20d and 9.21a–9.21d), Francisco Otoni (Fig. 9.17a), Sivana Romano Santos (Fig. 9.15) and Archt. Lelé's estatae (Adriana Filgueiras Lima) (Figs. 9.15a, 9.15b, 9.16, 9.17b, 9.18, 9.19a, 9.19b, 9.20a and 9.20b).

Rohinton Emmanuel (editor)
Glasgow, UK
August 2015

Contents

This page intentionally left blank

Author Affiliations

Rohinton Emmanuel, *School of Engineering and the Built Environment, Glasgow Caledonian University, UK*

Tzu-Ping Lin, *Department of Architecture, National Cheng Kung University, Tainan, Taiwan*

Edward Ng, *Chinese University of Hong Kong, Hong Kong SAR*

Denise H.S. Duarte, *Faculty of Architecture and Urbanism, University of Sao Paulo — FAUUSP, Brazil*

Erik Johansson, *Department of Architecture and Built Environment, Lund University, Sweden*

Narein Perera, *Department of Architecture, University of Moratuwa, Sri Lanka*

Renganathan Giridharan, *Kent School of Architecture, University of Kent, UK*

Patricia Drach, *Department of Architecture and Urbanism, School of Industrial Design, State University of Rio de Janeiro (UERJ) and Urban Engineering Programme, Federal University of Rio de Janeiro, Brazil*

Gerald Mills, *School of Geography, University College Dublin, Ireland*

This page intentionally left blank

Chapter 1

Introduction

Rohinton Emmanuel

The developing world has seen an urban transformation dramatic even by the standards of our urbanized world today. Urban population in the developing world has overtaken that of the developed world in less than a generation. However, the urban challenges within this region remain diverse: managing the near-saturated urbanization in Latin America (the world's most urbanized continent), rapid transformation into 'metacities' in Asia and the fastest rates of urbanization (albeit from a low base) in Africa. The urban growth in the tropics — much of it in the developing world — is particularly distinctive, from demographic, cultural and climatic points of view.

In parallel to the urban transformation (or because of it), the global climate is warming and the evidence is both unequivocal and unprecedented in recent times (i.e. decades to millennia, IPCC, 2014). While the general trend is towards a warmer climate, the regional variations are particularly problematic in the tropical regions. Irrespective of the future emission paths, South and Southeast Asia will experience unprecedented heat extremes while Central and Sub-Saharan Africa will experience extreme heat and drought even under a moderate ($<2°$C increase in global average temperature) global warming scenario (Schellnhuber *et al.*, 2013). Low-altitude locations in South Asia can expect changes in temperature extremes that are generally consistent with broad-scale warming (Revadekar *et al.*, 2013). Yan *et al.* (2002) showed a reduction of cold days in China over the 20th century while warm days have increased since 1961. In Central and Southern Asia, Klein *et al.* (2006) point out the increase in both the cold and warm tails of the distributions of daily minimum and maximum temperature between 1961 and 2000. Significant increases in the annual number of hot days and warm nights, and decreases in cold days and cold nights, were reported by Manton *et al.* (2001) and Griffiths *et al.* (2005) from Southeast Asia and the South Pacific. Additionally, increases in warm extremes were reported by Sheikh *et al.* (2015) across South Asia.

Much of the climate change risk is concentrated in urban areas. These include rising sea levels and storm surges, heat stress, extreme precipitation, inland and coastal flooding, landslides, drought, increased aridity, water scarcity and air pollution (Revi *et al.*, 2014). Given the current level of urban growth and the concentration of populations involved, climate change will interact with the urban risks in a variety of ways, some of which will exacerbate the level of climate risk (IPCC, 2014). Furthermore, there are health inequalities, especially in developing cities, that are further exacerbated by urban warming (cf. Campbell-Lendrum and Corvalán, 2007).

However, research on the augmentation of climate change effects by local urban warming (characterized by urban heat islands) remains weak. Initially, even the Intergovernmental Panel on Climate Change (IPCC) overlooked the role of cities both as a forcing factor as well as a key stakeholder in managing climate change (Hebbert and Jankovic, 2013). Even when the role of cities in what is termed the 'transformative adaptation' is acknowledged (as in the IPCC's 5th Assessment Report, cf. Revi *et al.*, 2014), strategies to tackle local warming barely receive a mention. To be fair, a key difficulty in untangling the urban warming from global climate change is the computational and parametric challenges associated with representing urban areas in climate models (Jin *et al.*, 2005; Grawe *et al.*, 2013). Additionally, translating future climate change projections at finer spatial scales relevant to cities typically uses statistical downscaling techniques to global climate models without modeling the urban areas themselves (Lemonsu *et al.*, 2013), a technique not without problems. Although the situation is continuing to improve (cf. Hebbert and Jankovic, 2013), much more still needs to be done to (a) ameliorate the urban heat island (UHI) effect and (b) use UHI mitigation as part of climate change adaptation (Emmanuel and Loconsole, 2015).

The amelioration of the heat island effect in the urban tropics is particularly weak on account of two facts. On the one hand, knowledge of tropical heat islands remains patchy and numerically weak (cf. Hung *et al.*, 2006; Roth, 2007). On the other, the proliferation of strategies focusing on heating-only climates (or the dual-mode heating-and-cooling-load climates) does not readily translate to cooling-only (or, soon-to-be cooling-only) regions.

Hence this book.

The premise of the book is that climate-sensitive design is a key enabler of climate change adaptation, especially in cities. This is particularly urgent in cities where the cooling load is the only or the principal design problem (i.e. the tropics). In the face of changing climate, climate-sensitive design in the tropics needs to recognize the limitations of naturally ventilated buildings (Ward *et al.*, 2012), facilitate the linking of the 'in' and 'out' (Emmanuel, 2010), optimize both the 'in' and the 'out' (Ng and Yuan, 2012) and enable 'situation-specific adaptive behavior' of urban dwellers (cf. Rijal *et al.*, 2012).

1.1 Antecedents

We begin at the commons.

In his address at the 150$^{\text{th}}$ anniversary celebrations of the Royal Institute of British Architects in 1984, Illich (1992) put forward the following thesis:

> *It would be a mistake to limit the effects of dwelling to the shaping of the interiors: what lies outside one's front door is as much shaped by dwelling, albeit in a different way. Inhabited land lies on both sides of the threshold; the threshold is like the pivot of the space that dwelling creates. On this side is home, and on the other lies the commons: the space that households inhabit is common... One demonstration of the destruction of commons is the degree to which our world has become uninhabitable. As the number of people increases, paradoxically we render the environment uninhabitable. (pp. 59–60)*

It is this threshold that acts as the linchpin linking the 'in' and 'out.'

The tradition of sharing exterior space — what Illich called the commons — is very strong in the tropics. "It takes time for the immigrant [from the tropics to the USA] to recognize that highways are neither streets nor paths but resources reserved for transportation... Many Puerto Ricans who arrive in New York need years to discover that sidewalks are not part of a plaza" (Illich, 1992: 59–60). If each citizen in the tropics is to be housed in 'comfort', as defined by a narrow range of environmental parameters, the cost in terms of energy use, urban sprawl and related ecological impacts will be enormous and, for these mostly economically poor nations, impossible to afford. Only by a careful design of the spaces around buildings to make them comfortable can designers and planners ever hope to achieve a reasonable way of dwelling in the densely populated parts of the tropics.

The ways people use the commons is conditioned by the climate and by traditions of the particular culture, for, as Illich says, "just as no two communities have the same style of dwelling, none can have the same commons" (Illich, 1992: 59). The tropical urban design challenge is to facilitate the use of commons in ways that are contextually appropriate.

Although the general causes of urban climate are the same across the world, the planning and building responses need not be; however, scholars and practitioners usually assume that strategies developed for temperate regions will work for the tropics as well. A review of literature related to urban design in the tropics (which, by the way, is scant) suggests a number of assumptions that need to be re-examined. For example, Givoni (1989), typical of many authors in this field, assumes the following:

- higher humidities in the tropics warrant design for higher wind movement to be the design priority;
- thermal comfort in the tropics depends more on air movement than on the reduction of solar radiation;
- night-time cooling occurs in the tropics.

This book is replete with examples of the fallacy of these statements. As long as radiation levels remain low, higher relative humidities and lower air movements are well within the thermal comfort range of most people in the tropics. The presence of dense vegetation makes green areas of tropical cities the best location in terms of thermal comfort, even if air movement is severely restricted. What is frustrating is that this was known from the very early days of heat island studies in the tropics, yet the ventilation-only fallacy remains. For example, one of the earliest heat island studies in Singapore — using the temperature–humidity index (THI) — found that when buildings are constructed of concrete and exposed to the elements, even the presence of very high wind movement does not provide thermal comfort. When they are shaded and surrounded by vegetation, comfort levels rise, despite the absence of high wind movement (Greenwood and Hill, 1968).

The principal climate variables altered by urban design are radiation and wind pattern; urban design in the tropics should take radiation control as the primary climatic design strategy. This too was implicit in tropical UHI studies from the beginning. Nieuwolt (1986), for example, shows that even at 'medium' air temperatures (30–35°C), natural ventilation becomes less effective as a thermal comfort strategy. Carmona (1986) concluded that in the urban tropics shading and heat avoidance in general have at least an equal effect on thermal comfort as natural ventilation.

Yet, urban heat amelioration continues to be shoehorned into conventional design and planning strategies. And, there are historical reasons for this persistence.

1.2 Climate and Tropical Design — a (Very) Short History of Misalignment

Before we embark on the appropriate strategies for climate-sensitive design in the urban tropics and the practicalities of conceiving and testing them, it is important to acknowledge how we got here. There are historical reasons for this and, lessons for future directions.

It is rather unfortunate that Europeans' early encounter with tropical climate coincided with a period when the miasmic theory of disease held sway in Europe. The miasmic theory held that miasma (bad air) is the cause of diseases such as cholera. Chang and King (2011) say thus:

> *Based on miasmic theory, it was reasoned that the hotter and more humid the climate, the faster the rate of putrefaction and, hence, the greater quantity of miasma. Taking England's climate as the norm, that of the Mediterranean stations occupied 'an intermediate position between England and those of the tropics: generally warm, at times depressing and variable, but not necessarily unhealthy to healthy people' (BHIC, 1863: A1). With regard to India, the tropical climate there was assumed to be 'hostile to human life, and to be especially deadly to the English race' (RCSSAI, 1863: xxxi). This basic threefold categorization, to be later summarized into a distinction between 'home', 'subtropical' and 'tropical', becomes a significant marker in the development of the episteme on tropical architecture. (p. 289)*

The miasmic theory led to a view of tropical climate as 'inherently unhealthy' even into the late 19$^{\text{th}}$ and early 20$^{\text{th}}$ centuries, despite the growing evidence of the microbial origins of many tropical diseases (Adamson, 2012).

However, even as the tropics were seen as 'unhealthy' or even 'dangerous', there was also the formulation that it was paradise. Ironically, this formulation of opposing tropes of danger and paradise (cf. Chee-Kien and Pieris, 2011) reinforced the pursuit of 'climate-sensitive design' as the answer, albeit answering the 'wrong' question.

While a focus on climate-sensitive design is a welcome attention in the tropics, the excessive 'fear' of tropical climate led to a peculiar view of the response to it. The upshot of this belief was an architectural response that could only be termed as 'airiness.' For example, Chang and King (2011) cite the Barrack and Hospital Improvement Commission (BHIC), established by the British government in 1861 to address unsanitary conditions in colonial barracks and hospitals, recommended that for 'home stations' (i.e. English locations) a minimum floor area of 60 sq. ft. (5.6 m^2) of superficial or floor area per person and 600 cu. ft. (17 m^3) of air space. For the Mediterranean stations, BHIC recommended a minimum of 70–75 sq. ft. and 750 cu. ft. (6.5–7 m^2 and 21 m^3 respectively) per person (BHIC, 1863: A3). For Indian and other tropical stations, the prescribed minimums were

80–100 sq. ft. and 1000–1500 cu. ft. (7.5–9.3 m^2 and 23–43 m^3 respectively) (Chang and King, 2011). This 'bias' of tropical architecture as primarily a matter of additional air space (Chang and King, 2011) continues to this day, irrespective of the fact that 'air' that is so circulated is hot and muggy! And made worse by the warming global climate and rapidly deteriorating urban climate in the tropics!

The planning and building 'improvements' to tropical conditions initiated in the 20^{th} century (e.g. the town-planning bylaws of W.J. Simpson in Singapore (Simpson, 1907, quoted by Chang and King, 2011) or the building bylaws of Sri Lanka) were meant to open the housing to sunlight and air, based on the opinions of sanitary experts.

Yet, voices of dissent against this orthodoxy existed almost as long as the sanitary experts were pushing the benefits of ventilation at the cost of all other strategies.

> *It appears, however, that in the East we have not been sufficiently attentive to the prevention of reflected heat and glare; a circumstance of infinitely greater consequence than the freest ventilation. Let us learn from the native. His habitation has very few apertures, and those high up. His floor, and the inside of the walls, are moistened two or three times a-day, with a solution of cow-dung in water, which, however disagreeable to the olfactories of an European, keeps the interior of the dwelling as cool as it is dark. Here he sits on his mat, enjoying his aqueous, but salutary beverage; and with such simple means and materials, counteracts the heat of the climate more effectually than the European, in his superb and costly edifice. (Johnson, 1818: 408)*

Added to this was the 'treatment' of the outdoors. In a recent survey of a vernacular settlement in South-central India (Marikkal Village, State of Andhra Pradesh), Indraganti (2010*a*) found the ancient village was organized in small dense clusters of compact tenements arranged along narrow streets and alleys that were rarely, if ever, aligned along the east-west axis (i.e. parallel to year-round tropical sun path). These shielded the building and ground from direct solar radiation and intense discomfort glare. The buildings themselves consisted of thick white walls, heavy roofs and small windows, incorporating locally available methods and materials, and reflected occupants status and activity.

Elsewhere, in Africa, indigenous urban forms were compact and green, relied on human-scale modes of transportation, and were safe and diverse (Asomani-Boateng, 2011).

Equally importantly, climate-sensitive design was accessible to both the rich and the poor alike:

> *The upper classes of natives, also, have not been inattentive to the prevention of reflected heat. The houses of Benares, for instance, are of solid stone, and generally six stories high, with small windows. The streets are so extremely narrow, that the sun has very little access to them; obviating thereby the disagreeable effects of glare. The windows are small, because, from the height of the houses, it would be impracticable to apply tatties during the hot winds; whereas, in low country-houses, or bungalows, they are large, in order to extend the refrigerating influence of the tatties. The dazzling whiteness of European houses in India, is not only inconvenient, but in some degree injurious, to the eyes, at least; and a verandah, entirely encompassing the mansion, would contribute greatly to the refrigeration of the interior apartments; the most comfortable of which, by the by, on the ground floor, used to be appropriated to the use of palankeens and lumber, but are now wisely converted into offices, &c. (Johnson, 1818: 409)*

Alas, this sensitivity to tropical climate is long extinguished in the professional circles. Air movement and especially occupant control of air movement (cf. Candido *et al.*, 2011) is now seen as vital to the successful application of adaptive approach to thermal comfort. However, little consideration is given to the outdoor conditions from which this air is moving indoors. What happens when the outdoor air continues to warm? There is evidence that under a warming climate even the vernacular design may not perform as well as needed (cf. Nguyen *et al.*, 2011).

The confounding of airiness with comfort in the tropics was not helped by a single-minded pursuit of narrowly defined notions of thermal comfort straightjacketed by a positivist worldview. Even when the evidence pointed to wide variations in acceptable thermal conditions in the tropics, standards and guidelines pursued an ever-elusive single number of temperature as the 'ideal' in the tropics. For example, in the Australian warm regions, Williamson (2013) reports of the early works by Hindmarsh and MacPherson (1962) who concluded from their extensive field-based research on thermal comfort that "the most generally preferred temperature was found to be 73°F (22.7°C) and a comfort zone in the range of 66°F (18.8°C) to 81°F (27.2°C), but... such a range is quite unacceptable in air-conditioning practice" (Williamson, 2013: 205). Others conflated the tropical revulsion of cold climates with European horror of warm temperatures (e.g. "temperatures below 70°F seem uncomfortable to tropical people, and above 80°F for cold temperate people" MacFarlane, 1958).

Perhaps the most helpful lesson to the tropics from the 'adaptive comfort movement' is the realization that thermal comfort is not a holy grail of one specific value but a moving target (cf. Nguyen *et al.*, 2012) and that certainly is the lived experience from the tropics.

1.3 Cooling, Pleasure and the Consequences of Climate Change

The task of cooling a building is very different from the act of heating for physical, social and economic reasons. One of the key differences between heating and cooling is in their respective load structure. Cooling requires the tackling of the increases in both the sensible as well as the latent loads (Kalveleage *et al.*, 2014). In other words it is not only the temperature but also the humidity that needs to be managed:

> *Removing humidity from air requires a phase change of water vapor, which in turn requires removal of a substantial amount of enthalpy, or thermodynamic energy. Lowering the temperature of humid air and maintaining a constant relative humidity, therefore, requires both reducing enthalpy of dry air and enthalpy due to the phase change of sufficient water vapor to keep the relative humidity constant.... A 1% increase in the climate saturate vapor pressure requires 0.5% in increased energy to counteract it. As a consequence, to maintain current human thermal comfort standards in buildings of the future, managing humidity will be more costly (in terms of energy consumption) than managing temperature. (Kalvelage et al., 2014: 379)*

Secondly, increased use of air conditioning in a warming world will only make the urban situation worse. A recent study in Malaysia found that every 1°C increment in outdoor temperature will cause a 2% drop in the coefficient of performance of split-type air conditioners (Yau and Pean, 2014). This is in sharp contrast to heating in urban areas, where wasted heat tends to reduce the heating load for surrounding buildings (Futcher *et al.*, 2013). In the case of air-conditioned 'coolth,' a simulation exercise on the effect of air conditioning use on street level temperature in Paris (at the conglomeration scale) found a systematic increase in street-level temperature, especially at night. The current increase in temperature due to air conditioner use was estimated to be 0.5°C but could be up to 2°C if the air conditioner use were to double (de Munck *et al.*, 2013: 210). While directly contributing to the heat island effect, greater use of air conditioning use also diminishes the efficacy of additional air conditioners that come on stream. Since air conditioners simply transfer heat from the indoors to the outdoors and their efficiency is a function of the temperature difference between the two, more air conditioners, especially in a vertical stack (as in multi-story buildings with each floor/unit having its own air conditioner), will increase the outdoor temperature surrounding the condenser. In a study in Singaporean multi-story housing estates, Bruelisauer *et al.* (2014) found up to a 13°C increase in the stack effect, leading to a 32% drop in air conditioner efficiency on floors 10 and above.

Thirdly, even when run on fossil fuels, heating could be provided by a variety of fuels (gas, oil etc.) that have lower carbon footprints than electricity (especially coal-fired electricity), which is the predominant source of power for most air conditioners. Thus, even a small increase in air conditioning use could vastly inflate global carbon emissions.

Fourth, much of the global heating demand is already manifest while much of the cooling demand is still latent. A recent review of heating and cooling energy use trends across the world (Ürge-Vorsatz *et al.*, 2015) found that regions dominated by heating load will see reduced or stagnant growth in energy use while warm regions dominated by cooling load will see exponential increase in cooling loads (see Table 1.1). This will be further exacerbated by trends within countries with heating and cooling demand — for example, the USA (Kalvelage *et al.*, 2014) where heating demand is expected

Table 1.1. Trends in global residential space heating and cooling demand (kW/m^2). (Source: based on Ürge-Vorsatz *et al.*, 2015)

	2010	2020	2030	2040	2050
Pacific OECD[1]	126.1	122.4	119.1	116.0	113.4
N. America	147.5	138.4	131.0	124.9	119.7
W. Europe	128.3	123.1	118.4	114.2	110.4
Central & E. Europe	152.6	148.1	144.8	141.8	139.1
Former Soviet Union	205.1	198.4	194.5	191.6	189.0
Latin America	63.3	60.2	59.5	59.3	59.6
Sub-Saharan Africa	56.2	53.4	52.9	53.0	53.4
Middle East and N. Africa	55.6	55.1	56.0	57.4	58.0
Centrally Planned Asia[2]	37.4	41.2	43.8	46.8	47.5
South Asia	60.1	77.1	85.0	89.2	88.2
Other Pacific Asia[3]	46.4	45.5	45.6	45.9	46.5

Note (see http://www.iiasa.ac.at/web/home/research/researchPrograms/Energy/MESSAGE-model-regions.en.html for naming conventions of world's regions)
[1]Australia, Japan, New Zealand
[2]Cambodia, China (incl. Hong Kong), Korea (DPR), Laos (PDR), Mongolia, Vietnam
[3]Southeast Asia and the Pacific Island states

to decrease while cooling demand will soar. A further confounding factor is that currently heating-load-dominated countries such as the UK (Jenkins *et al.*, 2013) and Ireland (Semmler *et al.*, 2010) are also expected to have significant cooling loads in the coming decades.

Finally, cooling itself is potentially more harmful from a global warming perspective than heating in that the refrigerants used in the process (mostly hydrofluorocarbons — HFCs) have greater global warming potential than CO_2. Thus, any leakage in the system could be a direct contributor to global warming, as opposed to heating where no such danger exists (Cox, 2012).

While the physics and the practicalities are more complex than heating, cooling — especially the mechanized variety — is also harder to divest of, given its social construct. The comfort of coolth is often seen as a sign of progress, initially a sign of luxury but eventually the fulfilment of desire. Heating does not have this association with 'luxury' since warmth was always seen as a primordial need (cf. Sivak, 2009). This is borne out by the difficulties air conditioning had in its early years of attempting to create a market in the United States, the social history of which is evocatively captured by Ackerman (2002). That 'coolth' is progress, is best captured by the following quotation:

> *Why have great inventions and advances in science and industry come from temperate zones? Because for centuries tropical heat has robbed men of energy and ambition. There was no air conditioning. So they took siestas, seeking relief from heat and stifling humidity.*
>
> *(from a Carrier Corporation advertisement from 1949–1950, reproduced in Ackerman, 2002: 18)*

This association of coolth with luxury and progress or, as Ackerman put it, "the prerogative if not the outright birth-right of the ruling classes" (Ackerman, 2002: 43) made it initially a desirable goal for the privileged, but within a very short few years, a vital necessity for many. Lest we conclude that such views are a particularly Western bias, the then Acting Minster for the Environment in Singapore, said in 2001, "air conditioning is one of the reasons why Singapore now enjoys the highest per capita GDP among countries on the tropical belt" (Ministry of Environment, 2001, quoted in Hitchings and Lee, 2008). Given this association of coolth with progress and well-being, an additional problem facing climate-sensitive design in the tropics is, that which does not *guarantee* coolth is seen as inferior, poor and ultimately, a denial of basic right (cf. Hitchings and Lee, 2008).

Things have moved a long way since the 1940s and 1950s when Americans needed to be convinced of their dire need for air conditioning. The link between coolth and economic progress is all the more evident in the rapidly growing economies of the world — especially in China and India. Urban air conditioning use in China grew from 2.3% to 61% between 1993 and 2003 — a growth rate of 39% per annum. In South Korea, it grew by a factor of five in about the same period (McNeil and Letschert, 2008). Room air conditioner purchases in India are currently growing at 20% per year, with about half of these purchases attributed to the residential sector (Cox, 2012).

> *Even if average incomes do not grow rapidly, dramatic increases in wealth of elites is already occurring. The real determining factor in air conditioner ownership will be the size of the middle class, that is, the*

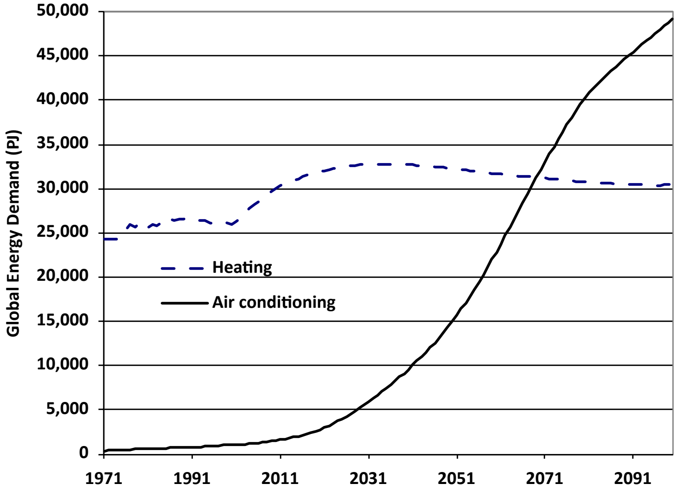


Figure 1.1. Global residential energy demand for heating and cooling. (Source: Isaac and van Vuuren, 2009)

> *number of households achieving a moderate level of affluence. (McNeil and Letschert, 2008: 13)*

Thus, we could expect economic development "to lead to an increasing cooling demand, a possible decrease of heating demand and a downward shift of the threshold temperature (at which heating demand ceases and cooling demand starts)" (Hekkenberg *et al.*, 2009) (see Fig. 1.1):

1. given the current global distribution of economic development and climate patterns (most developed economies need heating), much of the global heating demand is already manifest in energy demand, whereas much of the global cooling demand is still latent;
2. given the focus on heating in the developed world, greater improvement in heating efficiency has already occurred, whereas technological development and efficiency improvements in cooling are yet to be achieved;
3. greater economic development leads to more appliance use, which leads to greater internal gain, necessitating a lowering of threshold temperature at which cooling is demanded.

> *Energy demand for air conditioning is projected to increase rapidly over the whole 2000–2100 period, mostly driven by income growth. The associated CO_2 emissions for both heating and cooling increase from 0.8 GtC in 2000 to 2.2 GtC in 2100, i.e. about 12% of total CO_2 emissions from energy use (the strongest increase occurs in Asia). The net effect of climate change on global energy use and emissions is relatively small as decreases in heating are compensated for by increases in cooling. However, impacts on heating and cooling individually are considerable in this scenario, with heating energy demand decreased by 34% worldwide by 2100 as a result of climate change, and air-conditioning energy demand increased by 72%. At the regional scale considerable impacts can be seen, particularly in South Asia, where energy demand for residential air conditioning could increase by around 50% due to climate change, compared with the situation without climate change. (Isaac and van Vuuren, 2009)*

Figure 1.2 shows the theoretical maximum air conditioner use (assuming the US case to be the exemplar) developed originally by Sailor and Pavlova (2003) and modified by McNeil and Letschert (2008). Given the typical level of cooling degree days (CDD) in the tropics (in the region of 2,000–4,000 especially in the warm, humid tropics — see Table 1.2) the theoretical maximum air conditioning use is 100%, but this will be tempered by the level income. For example, while the current use of air conditioning is minimal (less than 2%), the potential cooling demand in metropolitan Mumbai is about 24% of the demand for the entire United States (Sivak, 2009). This is further illustrated in Fig. 1.3, which shows that countries and regions that have higher CDD typically have low income levels while high income regions and countries are low in cooling load.

Herein lies the gist of the approaching air conditioning Armageddon in the tropics: the climate 'requires' air conditioning and the rising income will 'inevitably' demand it. Or, will it?

Three current phenomena, especially seen in affluent Asia, point to an answer in the affirmative: expectation, enhanced opportunity and enhanced sensitivity. As affluence spreads, coolth come to be expected; life is then organized around this expectation to provide greater opportunity for an air-conditioned existence and soon bodies become ultra-sensitive to even minute variance away from mechanically powered coolth (cf. Han *et al.*, 2009).

Table 1.2. Cooling degree days in typical warm, humid tropical cities. (Source: based on data from http://www.weatherbase.com)

	Annual CDD
Abidjan	2,976
Accra	3,037
Bangkok	3,588
Cartagena	3,315
Chennai	3,730
Colombo	3,377
Dhaka	2,832
Fortaleza, Bahia	2,158
Freetown	2,623
Ho Chi Minh City	3,437
Jakarta	3,135
Kuala Lumpur	3,224
Lagos	3,007
Manila	3,225
Mombasa	2,826
Mumbai	3,207
Recife	2,595
Rio de Janeiro	2,128
Salvador	2,531
Singapore	3,316
Thiruvananthapuram	3,172
Victoria, Seychelles	3,163

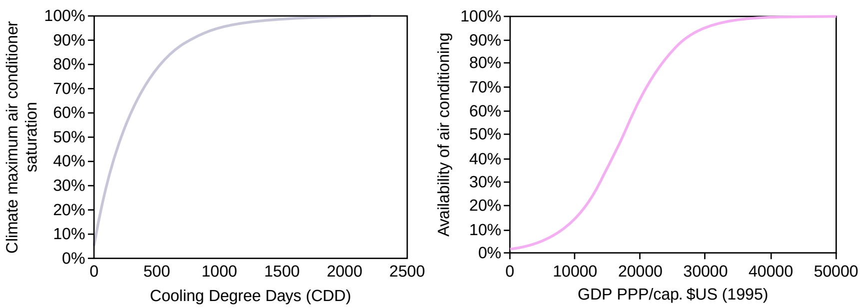


Figure 1.2. Theoretical maximum air conditioner saturation as a function climate (left) and maximum air conditioner saturation as a function of income (right). (Source: Isaac and van Vuuren, 2009)

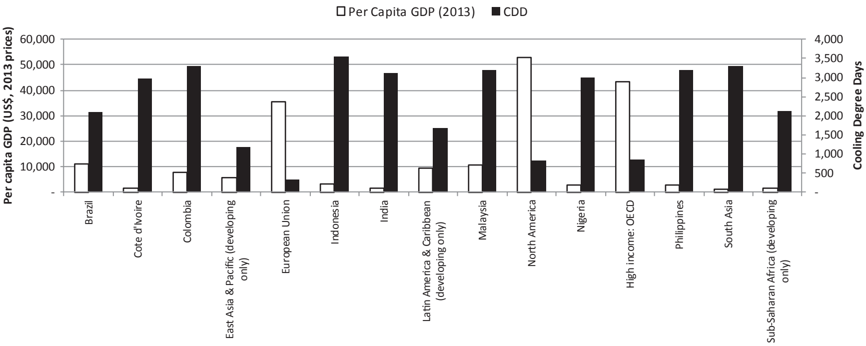


Figure 1.3. Income vs. cooling load comparison. (Source: drawn from data available at: World Bank, 2015 (per capita income) and McNeil and Letschert, 2008 (Cooling Degree Days))

All these point to the conclusion that an increasingly prosperous tropics (especially in Asia and South America) is likely to tread the path of mechanized coolth to the detriment of global energy use and attendant ills.

1.4 The Current Impasse in Climate-Sensitive Design in the Tropics

In spite of the changes to tropical climate both at the global/regional level as well as at the city level, there is little evidence that climate-sensitive design has received any greater attention than it had ever had. "Cities which understand and manage their local climate have a head start in responding to global climate change" (Hebbert and Jankovic, 2013). However, three broad categories of barriers need to be overcome if we are to enhance the reputation of climate-sensitive design and take its development further: technical, institutional and cultural.

1.4.1 *Technical limitations*

Nicol and Stevenson (2013) suggested a four-pronged strategy as a way forward in designing the built environment for comfort and to adapt to the changing climate:

- rely as little as possible on the availability of cheap, plentiful energy;
- provide an environment that affords maximum adjustability;
- know the temperature expectations in particular kinds of buildings and circumstances;
- plan the adaptive opportunities that buildings should provide to inhabitants (Nicol and Stevenson, 2013: 256).

As we have shown in the preceding discussions, the problem (particularly in the changing climatic regimes in tropics) is that our ability to provide passive (i.e. without the use of energy) adaptive opportunities at temperatures tropical dwellers *expect* is steadily diminishing. This is so even if we are able to provide maximum adjustability. Herein lies the crux of the technical problem: the tropics (especially the urban tropics) have warmed to an extent that passive, building-level strategies to tackle it have been more or less exhausted. Furthermore, the abilities of traditional approaches to climate-sensitive design appear less effective under a changing and extreme climate (Nguyen *et al.*, 2011).

The adaptive model of thermal comfort popularized the notion of thermal comfort as a function of external temperature:

> *It is in principle possible to design and operate buildings that provide comfort in the free-running mode at least within a range of prevailing mean outdoor temperature from* 10°*C to* 30°*C. (Humphreys et al., 2013)*

Will it be possible to achieve thermal comfort if the tropics continue to warm? Even when the average outdoor temperature exceeds 30°C?

> *At rather high temperature and humidity, adaptive actions do not seem very effective and the comfort range is, consequently, slightly smaller than that under more favorable conditions. (Nguyen et al., 2012)*

In other words, is adaptive approach an *ad infinitum* possibility?

> *...adaptive model is best suited to explain occupant comfort during times of natural ventilation within the same building. When operating in AC mode, Fanger's PMV–PPD model shows good correlations with observed thermal sensations. (Deuble and de Dear, 2012)*

Is this true in the tropics? What form(s) should such combinations take?

> *control of solar gains will always lead to greater direct ventilative and night cooling benefits. Other considerations such as humidity control for reasons other than thermal comfort require careful consideration and analysis. (Emmerich et al., 2011)*

In other words, the technical requirements of climate-sensitive design appear to be approaching the impossible in the tropics, as the background climate continues to warm. We need agreement on the 'what' (i.e. the scope) of climate-sensitive design.

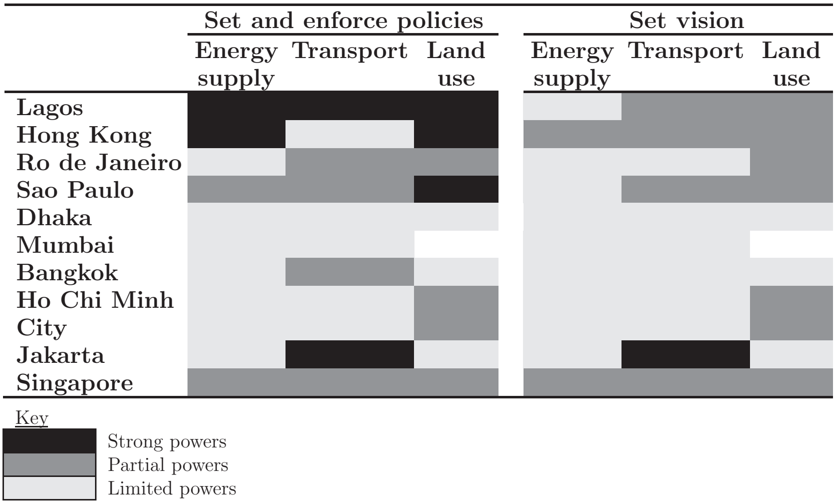
1.4.2 *Institutional/governance issues*

Equally importantly, the 'how' of climate-sensitive design also needs greater attention. Urban design, unlike the design of individual buildings and areas, concerns that which belongs to all and is therefore subject to the 'tragedy of the commons' (Hardin, 1968). The promotion of good urban design therefore needs strong institutional underpinning. This appears to be the lesson from those cities that have successfully utilized local knowledge of their climatic context for better urban planning (cf. Hebbert and Jankovic, 2013).

> *The criteria of minimum energy use and maximum thermal comfort are conflicting: pressing for a low energy use, means relaxing the thermal comfort requirements. A compromise has to be reached based on people's priorities. (Sourbron and Helsen, 2011)*

On its own, climate-sensitive design lacks the clout and capacity to grab and hold the attention of key decision makers. This is especially the case in tropical cities where the problem of overcrowding and the more immediate risks associated with climate change (such as flooding, coastal erosion, dust storms and drought) are ever more pressing. The embedding of climate-sensitive design into everyday planning decisions will be important to success. Towards this end, climate-sensitive planning needs to be linked to broader agendas such as poverty alleviation, economic development and urban regeneration.

Table 1.3. Level of autonomy among major tropical cities in controlling climate change drivers. (Source: based on data from C40Cities Climate Leadership Group (http://www.c40.org/))



Furthermore, innovative institutional arrangements are needed to link on-the-ground scientific expertise to the needs and requirements of local city decision-makers (cf. Rosenzweig *et al.*, 2010). In this connection the governance arrangements in cities too needs consideration: who will champion climate-sensitive design? Whose priorities are dominant in urban contexts and what are the implications of this to climate-sensitive design? Finally, how 'autonomous' are cities in being able to chart their own adaptation destiny? A careful look at the C40Cities — a group of major cities with strong commitment to climate change matters — shows (Table 1.3) that many of the tropical megacities for which data are available have limited or only partial powers to set and enforce policies and vision to control major climate change drivers (energy supply, transport and land use). This is especially the case with respect to their ability to set the vision, pointing to limited ability of major cities to control their climate action destinies.

Climate-sensitive design and, more broadly, sustainable urban design often neglect the city as a complex of social, economic, cultural and political concerns and, consequently, very little progress has been made in terms of synthesizing these myriad and often conflicting aims (cf. Vallance and Perkins, 2010).

1.4.3 *Cultural barriers*

Openness to passive climate-sensitive design depends on socioeconomic status. Those who can afford the energy expenditure (on air conditioning, for example) tend to be 'thermally indulgent' to the point of low tolerance for thermal displeasure (Indraganti, 2010*b*). Additionally, cultural practices and preferences/attitudes lead to 'restrained adaptive opportunity' (Indraganti, 2010*c*). An immersion in greater comfort (i.e. greater pleasure) appears to hyper-sensitize us to a point of inability to cope with natural variations in temperature. This is the other edge of the double-edged sword that is mechanized comfort. While the use of air conditioning undoubtedly leads to 'superior' comfort (and is a 'birthright' of all tropical dwellers!) it also diminishes the coping mechanisms of tropical dwellers. There appears no compromise, or is there?

Climate-sensitive design could help, but unfortunately it had hitherto largely remained an elite project in the tropics, where the vast majority of buildings continue to be relegated to the intolerable-to-barely-passable margins. No context exists for the enjoyment of an otherwise pleasant climate by a majority of citizens.

> *Can architecture ... maintain its current detachment from the industry and the urban context? Can buildings in developing countries continue to be viewed as* objets d'art *or do architects have to concede to the complex urban and rural systems within which they are to be situated? After 50 years of discourse, debate and dissemination, the tropical agenda seemed to have retreated into isolated individualistic building practice, localized only by an apparent engagement with climate. Picture-book tropical houses and resort hotels photographed within their high boundary walls replicated a colonial history of economic divisions. With rapid urbanization and the growing awareness of political inequities, such utopian positions and the continued sustenance of the descriptor 'tropical' may now seem unconscionable. (Chee-Kien and Pieris, 2011: 378–379).*

As seen previously, mechanical coolth has the additional association with progress and development. The results of these two ('tropical architecture' as a coffee table extravaganza of the elite made possible by large, verdant sites and air conditioning the symbol of progress and development for all other buildings) militate against the popularization of climate-sensitive design as the norm in the tropics. Climate-sensitive urban design needs to be seen as the contextual enabler that makes thermal comfort possible for individual buildings, with or without the use of air conditioning.

> *Comfort is socially and culturally constructed and thus may be partially unconstructed, attempts to reduce greenhouse gas emissions may come at the expense of workers who are already stressed with multiple demands and limited refuge. (Moezzi, 2009)*

Another issue that rarely gets a mention is the gendered dimensions of thermal comfort in the tropics. There is evidence that females are more likely than males (74% more likely) to show dissatisfaction with a given thermal environment, especially in cooler ones. Their tolerance of warm discomfort is greater (Karjalainen, 2012). Could the ever greater push for coolth have a gendered consequence? What are the consequences to the urban outdoors?

1.5 Where Do We Go from Here?

It is said that thermal comfort (in temperate climates) needs to be 're-contextualized' in light of climate change (Cole *et al.*, 2008). This often means a more inclusive, inhabitant-controlled, flexible notion of thermal comfort that allows for 'inhabitant agency' (Cole *et al.*, 2008) but questions remain as to its applicability in the high-density and rapidly growing and generally resource-poor urban tropics. We have shown that the nature of tropical thermal comfort, especially in light of changing urban climate, is not always achievable even with 'inhabitant agency,' at least not all of the time. What therefore must we do in the tropics?

This book proposes that tropical climates, especially in their cities, could only be made comfortable (and places for human thriving) by climatizing the urban realm. We do not expect that doing so will eliminate the need for air conditioning. Far from it: climate-sensitive urban design is a crucial enabler of outdoor living, even in the face of climate change. This could create the condition for alternate ways of enhancing urban quality of life, while individual buildings may or may not need additional coolth.

> *It is only through a deliberately expansive approach to the ways in which bodies, clothing and immediate climate are locally interlinked that we produce the richest sense of the processes currently responsible for a much wider retreat into indoor social spaces. (Hitchings and Lee, 2008: 263)*

The book proposes an 'expansive approach' at the scale of neighborhoods and cities so as to create suitable local climates to enable bodies to be at ease in the outdoors, thus able to cope with a changing climate even if the indoors continue to warm. That the latter might still be air-conditioned is a matter of when, not if. Our hope is that an enabling environment could be created at the neighborhood scale, for a low-energy-intensity (therefore low-carbon) future, so that when tropical dwellers wake up (or rudely awaken) from their fossil-fuel-induced and air-conditioned stupor there could still be high quality life.

1.6 Structure of the Book

This book is in three parts. Part I presents the philosophical basis for a contemporary tropical urbanism distinguished by its climate sensitivity. Two chapters, including this introduction, set the context for climate-sensitive design in the tropics by delineating the historical reasons, challenges and opportunities for tropical climate-sensitive design. In the second chapter we will explore the limits to thermal comfort in the tropics and propose a reformulation of 'thermal pleasure' in the tropics that is centered on the outdoors. It will take the form of promotion of shading and ventilation together with the use of water. More importantly, it will highlight the important role of urban design in managing and promoting a higher quality of urban life even in the face of a warming climate. A key to this is the linking of the 'in' and the 'out' of the buildings, together with activity-pattern-based approach to urban thermal comfort as the thread connecting thermal pleasure across space and time in tropical cities.

The second part is the meat of the book, providing specific design strategies, modeling and measurement approaches to climate-sensitive design in the tropics. Three design approaches (shading, ventilation and the use of vegetation), two protocols (comfort and local climate zones) and a primer on evidence gathering (modeling) are covered. The section begins with a chapter on shading in public places. It provides a rich tapestry of anecdotal as well as hard-science-based evidence for shade preference in the tropics and ways to achieve it in public places. Shade is a key strategy to create thriving public places in the tropics. Shade from a careful arrangement of buildings as well as trees could create convivial public places that could enhance outdoor livability in tropical cities, a key approach to overcoming the overheating problem in the face of rapid urban growth. However, shading without ventilation could never achieve thermal comfort by passive means alone. Chapter 4 focuses on achieving urban air ventilation, especially in high-density tropical cities. Given the notoriously fickle nature of tropical wind and the mathematical and computing intensities of its quantification, the focus of this chapter is to set the ground for a ventilation assignment from an urban planning point of view. A sample mapping exercise as well as future directions in this rapidly evolving area are presented.

The cooling effect of vegetation depends on urban morphology and local climate as well as plant characteristics, and these aspects of urban vegetation are the focus of Chapter 5. One of the defining characteristics of tropical green cover is its seemingly small differences in air temperature; however, significant reductions in mean radiant temperature are possible with urban greenery, and this chapter presents both the evidence for the effect and the planning and design parameters that maximize such radiant cooling in tropical cities. Nevertheless, urban green infrastructures typically have very localized cooling effects and a long-term approach to a dispersed green infrastructure across cities is needed to better cope with the overheating problem, especially to face the extremes in overheating that will inevitably follow when heat islands are superimposed on a warming background climate.

The quantification of comfort in urban environments remains a difficult task even as we see a proliferation of comfort indices. Chapter 6 attempts to make sense of this by both returning to the basics (energy balance of human body) as well as critically evaluating the performance of a myriad of comfort indices. More crucially, this chapter presents protocols for the measurement of thermal comfort in the tropics and the common pitfalls to be avoided. The semantics of ‘neutral’ and ‘preferred’ temperatures from a tropical point of view are discussed in detail.

In the final analysis the planning exercise to manage local climate in cities requires their mapping, and one such technique that is gaining increasing attention is the so-called ‘local climate zone’ (LCZ) approach. Chapter 7 explores the protocols as well as challenges facing tropical cities in using an LCZ-based approach to local climate mapping. A case study from Colombo, Sri Lanka highlights both the possibilities for mapping and planning action on the one hand and data challenges on the other. This mapping action, however, needs to be augmented by modeling to derive planning and design strategies as well as chart out development trajectories. Thus, Chapter Eight presents both the energetics of urban tropics and its modeling. Options for modeling readily available for the tropics are discussed together with challenges in parametrization and how to overcome these. Future direction in this fast-changing area of research is also presented.

The protocols in the second part of book — urban thermal comfort (Chapter 6), urban climate mapping using the LCZ approach (Chapter 7) and urban climate modeling (Chapter 8) are critical to tropical urban climate researchers. Given the confusions surrounding thermal comfort in the tropics as well as the typically patchy availability of low quality data on urban morphology, we clarify the comfort goals as well as mapping and modeling challenges using low data-intensive, but highly localized approaches to study these, in the hope of advancing the study of tropical urban climate in this challenging but crucial region.

The third and final section of the book provides exemplars of climate-sensitive urban design and presents them within the climate change agenda. We begin by exploring that rarest of finds — built examples of tropical urbanity that incorporates the best in shading, ventilation and assiduous use of vegetation. A quick tour of 'traditional' approaches and their 'modern' interpretations are shown in Chapter 9. Built examples at scales larger than individual buildings are presented from Brazil and elsewhere. The role of climate-sensitive context in making possible a humane-form of thermal comfort within buildings is also highlighted.

However, in the final analysis, climate-sensitive urban planning and design in the tropics is not just about techniques and exemplars but also the *zeitgeist* — climate change and adaptation/mitigation. The final chapter presents an agenda for the integration of urban climate-sensitive design as a vehicle for climate change mitigation (and/or adaptation), especially in the tropics. The science of urban climate change and policy responses to it are juxtaposed with global climate change science and its policy responses. The role of cities in tackling both these changes is highlighted. While the existing planning systems in cities could help in implementing global climate change mitigation/adaptation policies, it is important that such policies be complementary, in order to tackle both the global as well as the urban climate change. Towards this end, the last chapter highlights the 'hierarchy of climate scales' and anthropogenic drivers.

The role of cities in both mitigating the negative consequences of climate change and in learning to live with them is only beginning to be appreciated by the global climate change policy and planning communities. The problem is all the more urgent in tropical cities. An understanding of urban climates is therefore needed to integrate global climate change actions into planning and design. It is hoped that this book will add to a small but growing chorus of voices that both set the agenda as well as point the way forward to action in this increasingly central task from a region that faces both the greatest threat but also offers the widest array of opportunities for action.

References

Ackerman, M.E. (2002). *Cool Comfort: America's Romance with Air Conditioning*, Washington: Smithsonian Institution Press.

Adamson, G.C.D. (2012). 'The languor of the hot weather': everyday perspectives on weather and climate in colonial Bombay, 1819–1828, *Journal of Historical Geography*, **38**, 143–154.

Asomani-Boateng, R. (2011). Borrowing from the past to sustain the present and the future: indigenous African urban forms, architecture, and sustainable urban development in contemporary Africa, *Journal of Urbanism*, **4**(3), 239–262.

Barrack and Hospital Improvement Commission (BHIC), (1863). *Report of the Barrack and Hospital Improvement Commission on the Sanitary Condition and Improvement of the Mediterranean Stations*. George Edward Eyre and William Spottiswoode, London.

Bruelisauer, M., Meggers, F., Saber, E. *et al.* (2014). Stuck in a stack — Temperature measurements of the microclimate around split type condensing units in a high rise building in Singapore, *Energy and Buildings*, **71**, 28–37.

Campbell-Lendrum, D. and Corvalán, C. (2007). Climate change and developing-country cities: Implications for environmental health and equity, *Journal of Urban Health*, **84**(1), i109–i117.

Candido, C., Lamberts, R., de Dear, R. *et al.* (2011). Towards a Brazilian standard for naturally ventilated buildings: guidelines for thermal and air movement acceptability, *Building Research & Information*, **39**, 145–153.

Carmona, L.S. de (1986). "Human Comfort in the Urban Tropics", in *Urban Climatology and its Applications with Special Regard to Tropical Areas*. Proceedings of the Technical Conference held in Mexico City, 1984, World Meteorological Organization, Geneva.

Chang, J.-H. and King, A.D. (2011). Towards a genealogy of tropical architecture: Historical fragments of power-knowledge, built environment and climate in the British colonial territories, *Singapore Journal of Tropical Geography*, **32**, 283–300.

Chee-Kien, L. and Pieris, A. (2011). Post-tropical/post-tsunami: Climate and architectural discourse in South and Southeast Asia, *Singapore Journal of Tropical Geography*, **32**(3), 365–381.

Cole, R.J., Robinson, J., Brown, Z. *et al.* (2008). Re-contextualizing the notion of comfort, *Building Research & Information*, **36**, 323–336.

Cox, S. (2012). "Cooling a Warming Planet: A Global Air Conditioning Surge", Yale Environment 360, July 10, http://e360.yale.edu/feature/cooling_a_warming_planet_a_global_air_conditioning_surge/2550.

de Munck, C., Pigeon, G., Masson, V. *et al.* (2013). How much can air conditioning increase air temperatures for a city like Paris, France?, *International Journal of Climatology*, **33**, 210–227.

Deuble, M. P., de Dear, R. J. (2012) Green occupants for green buildings: The missing link?, *Building and Environment*, **56**, 21–27.

Emmanuel, R. (2010). "Linking the in and out: new comfort goals for the rapidly urbanizing equatorial tropical megacities in a changing climate," *Windsor 2010 Conference, Adapting to change: new thinking on comfort*, Network for Comfort and Energy Use in Buildings (NCEUB), April 2010, Windsor, UK. DOI: 10.13140/2.1.5050.5921.

Emmanuel, R., Loconsole, A. (2015). Green infrastructure as an adaptation approach to tackle urban overheating in the Glasgow Clyde Valley Region, *Landscape and Urban Planning*, **138**, 71–86.

Emmerich, S.J., Polidoro, B. and Axley, J.W. (2011). Impact of adaptive thermal comfort on climatic suitability of natural ventilation in office buildings, *Energy and Buildings*, **43**, 2101–2107.

Futcher, J.A., Kershaw, T. and Mills, G. (2013). Urban form and function as building performance parameters, *Building and Environment*, **62**, 112–123.

Givoni, B. (1989). Urban Design in Different Climates, *World Climate Applications Programme*, (WCAP) No. 10. WMO/TD-No. 346, World Meteorological Organization, Geneva.

Greenwood, P., Hill, R.D. (1968). Buildings and Climate in Singapore, *Journal of Tropical Geography*, **26**, 37–47.

Grawe, D., Thompson, H.L., Salmond, J.A., Cai, X.-M., Schlünzen, K.H. (2013). Modelling the impact of urbanisation on regional climate in the Greater London Area, *Int. J. Climatol.*, **33**, 2388–2401.

Griffiths, G.M., Chambers, L.E., Haylock, M.R. *et al.* (2005). Change in mean temperature as a predictor of extreme temperature change in the Asia–Pacific region, *International Journal of Climatology*, **25**, 1301–1330.

Han, J., Yang, W., Zhou, J. *et al.* (2009). A comparative analysis of urban and rural residential thermal comfort under natural ventilation environment, *Energy and Buildings*, **41**, 139–145.

Hardin, G. (1968). The tragedy of the commons, *Science*, **162**(3859), 1243–1248.

Hebbert, M. and Jankovic, V. (2013). Cities and climate change: the precedents and why they matter, *Urban Studies*, **50**, 1332–1347.

Hekkenberg, M., Moll, H.C. and Schoot Uiterkamp, A.J.M. (2009). Dynamic temperature dependence patterns in future energy demand models in the context of climate change, *Energy*, **34**(11), 1797–1806.

Hindmarsh, M.E. and MacPherson, R.K. (1962). Thermal comfort in Australia, *Australian Journal of Science*, **24**(8), 335–339.

Hitchings, R. and Lee, S.-J. (2008). Air conditioning and the material culture of routine human encasement: the case of young people in Singapore, *Journal of Material Culture*, **13**, 251–265.

Humphreys, M.A., Rijal, H.B. and Nicol, J.F. (2013). Updating the adaptive relation between climate and comfort indoors; new insights and an extended database, *Building and Environment*, **63**, 40–55.

Hung, T., Uchihama, D., Ochi, S. *et al.* (2006). Assessment with satellite data of the urban heat island effects in Asian mega cities, *International Journal of Applied Earth Observation and Geoinformation*, **8**(1), 34–48.

Illich, I. (1992). *In the Mirror of the Past: Lectures and Addresses, 1978–1990*, Marion Boyars, New York, NY.

Indraganti, M. (2010*a*). Understanding the climate sensitive architecture of Marikal, a village in Telangana region in Andhra Pradesh, India, *Building and Environment*, **45**, 2709–2722.

Indraganti, M. (2010*b*). Adaptive use of natural ventilation for thermal comfort in Indian apartments, *Building and Environment*, **45**, 1490–1507.

Indraganti, M. (2010*c*). Behavioural adaptation and the use of environmental controls in summer for thermal comfort in apartments in India, *Energy and Buildings*, **42**, 1019–1025.

IPCC. (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R. K. Pachauri and L. A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Isaac, M. and van Vuuren, D.P. (2009). Modeling global residential sector energy demand for heating and air conditioning in the context of climate change, *Energy Policy*, **37**, 507–521.

Jenkins, D.P., Gul, M. and Patidar, S. (2013). Probabilistic future cooling loads for mechanically cooled offices, *Energy and Buildings*, **66**, 57–65.

Jin M., R.E. Dickinson, D.-L. Zhang, (2005). The Footprint of Urban Areas on Global Climate as Characterized by MODIS, *J. Climate*, **18**, 1551–1565.

Johnson, J. (1818). *The Influence of Tropical Climates on European Constitutions, 2nd ed.*, Portsmouth, self-published.

Kalvelage, K., Passe, U., Rabideau, S., Takle, E. S. (2014). Changing climate: The effects on energy demand and human comfort, *Energy and Buildings*, **76**, 373–380.

Karjalainen, S. (2012). Thermal comfort and gender: a literature review, *Indoor Air*, **22**, 96–109.

Klein, T., Peterson, T.C., Quadir, D.A. *et al.* (2006). Changes in daily temperature and precipitation extremes in central and South Asia, *Journal of Geophysical Research*, **111**, D16105.

Lemonsu, A., Kounkou-Arnaud, R., Desplat, J., Salagnac, J.-L., Masson, V. (2013). Evolution of the Parisian urban climate under a global changing climate, *Climatic Change*, **116**, 679–692.

Lowry, W.P. (1967). The climate of cities, *Scientific American*, **217**:2, 15–24.

MacFarlane, W.V. (1958). Thermal Comfort Zones, *Architectural Science Review*, **1**, 1–14.

Manton, M.J., Della-Marta, P.M., Haylock, M.R. *et al.* (2015). Trends in extreme daily rainfall and temperature in southeast Asia and the South Pacific: 1916–1998, *International Journal of Climatology*, **21**, 269–284.

McNeil, M.A. and Letschert, V.E. (2008). Future Air Conditioning Energy Consumption in Developing Countries and What Can Be Done About It: The Potential of Efficiency in the Residential Sector, Lawrence Berkeley National Laboratory, Berkeley, CA, available at: http://escholarship.org/uc/item/64f9r6wr (accessed 19 June 2014).

Ministry of Environment speech release, 'Address by Mr Lim Swee Say at the ASHRAE Singapore Chapter's 19th Installation Dinner and Dance', News R/No. 59/2001, 28 April 2001.

Moezzi, M. (2009). Are comfort expectations of building occupants too high?, *Building Research & Information*, **37**, 79–83.

Ng, E. and Yuan, C. (2012). Policies and technicalities providing natural ventilation to domestic spaces for high-density tropical living in Hong Kong, *Architectural Science Review*, **55**(1), 61–70.

Nguyen, A.-T., Singh, M.K. and Reiter, S. (2012). An adaptive thermal comfort model for hot humid South-East Asia, *Building and Environment*, **56**, 291–300.

Nguyen, A.-T., Tran, Q.-B., Tran, D.-B. *et al.* (2011). An investigation on climate responsive design strategies of vernacular housing in Vietnam, *Building and Environment*, **46**, 2088–2106.

Nicol, F. and Stevenson, F. (2013). Adaptive comfort in an unpredictable world, *Building Research & Information*, **41**(3), 255–258.

Nieuwolt, S. (1986). "Design for Climate in Hot, Humid Cities", in *Urban Climatology and its Applications with Special Regard to Tropical Areas*. Proc. Tech. Conf. held in Mexico City, 1984, World Meteorological Organization, Geneva.

Revadekar, J.V., Hameed, S., Collins, D. *et al.* (2013). Impact of altitude and latitude on changes in temperature extremes over South Asia during 1971–2000, *International Journal of Climatology*, **33**, 199–209.

Revi, A., Satterthwaite, D., Aragon-Durand, F. *et al.* (2014). Towards transformative adaptation in cities: The IPCC's Fifth Assessment, *Environment and Urbanization*, **26**(1), 11–28.

Rijal, H.B., Tuohy, P., Humphreys, M.A. *et al.* (2012). Considering the impact of situation-specific motivations and constraints in the design of naturally ventilated and hybrid buildings, *Architectural Science Review*, **55**(1), 35–48.

Rosenzweig, C., Solecki, W., Hammer, S.A. *et al.* (2010). Cities lead the way in climate-change action, *Nature*, **467**, 909–911.

Roth, M. (2007). Review of urban climate research in (sub)tropical regions, *Int. J. Climatology*, **27**, 1859–1873.

Sailor, D.J. and Pavlova, A.A. (2003). Air conditioning market saturation and long-term response of residential cooling energy demand to climate change, *Energy*, **28**, 941–951.

Schellnhuber, H.J., Hare, B., Serdeczny, O. *et al.* (2013). "Turn down the heat: climate extremes, regional impacts, and the case for resilience — full report", World Bank, Washington DC, available at: http://documents.worldbank.org/curated/en/2013/06/17862361/turn-down-heat-climate-extremes-regional-impacts-case-resilience-full-report, (last accessed 19.06.2014).

Semmler, T., McGrath, R., Steele-Dunne, S. *et al.* (2010). Influence of climate change on heating and cooling energy demand in Ireland, *Int. J. Climatol.*, **30**(10), 1502–1511, http://dx.doi.org/10.1002/joc.1997.

Sheikh, M.M., Manzoor, N., Ashraf, J., Adnan, M., Collins, D., Hameed, S., Manton, M.J., Ahmed, A.U., Baidya, S.K., Borgaonkar, H.P., Islam, N., Jayasinghearachchi, D., Kothawale, D.R., Premalal, K.H.M.S., Revadekar, J.V. and Shrestha, M.L. (2015). Trends in extreme daily rainfall and temperature indices over South Asia, *International Journal of Climatology*, **35**(7), 1625–1637.

Sivak, M. (2009). Potential energy demand for cooling in the 50 largest metropolitan areas of the world: Implications for developing countries, *Energy Policy*, **37**, 1382–1384.

Sourbron, M. and Helsen, L. (2011). Evaluation of adaptive thermal comfort models in moderate climates and their impact on energy use in office buildings, *Energy and Buildings*, **43**, 423–432.

Ürge-Vorsatz, D., Cabeza, L.F., Serrano, S. *et al.* (2015). Heating and cooling energy trends and drivers in buildings, *Renewable and Sustainable Energy Reviews*, **41**, 85–98.

Vallance, S. and Perkins, H. (2010). Is another city possible? Towards an urbanized sustainability, *City*, **14**(4), 448–456.

Ward, J.K., Wall, J. and Perfumo, C. (2012). Environmentally active buildings: the controls challenge, *Architectural Science Review*, **55**(1), 26–34.

Williamson, T.J. (2013). Designing houses for the Australian climate: the early research, *Architectural Science Review*, **56**, 197–207.

Yan, Z., Jones, P.D., Davies, T.D. *et al.* (2002). Trends of extreme temperatures in Europe and China based on daily observations, *Climatic Change*, **53**, 355–392.

Yau, Y.H. and Pean, H.L. (2014). The performance study of a split type air conditioning system in the tropics, as affected by weather, *Energy and Buildings*, **72**, 1–7.

Chapter 2

Achieving thermal pleasure in tropical urban outdoors

Rohinton Emmanuel

We showed in the previous chapter that growing urbanization and increasing prosperity in the tropical region appears to lead to greater thermal comfort expectation. The question remains as to how to provide thermal comfort at the 'right' level of energy expenditure. Could the active provision of thermal comfort be combined with the adaptive approach? (i.e. greater tolerance of thermal comfort variations across seasons/time of day/functions while combining the building-oriented thermal comfort approach with 'urban design'?) How does one 'climate-proof' tropical neighborhoods so that the possibility for thermal comfort at building-scale is enhanced?

Urban shading, ventilation corridors based on air ventilation assessment, and green infrastructure are the approaches this book takes, and these are seen as creating an 'enabling urban design context' for individual buildings to achieve greater comfort with as little energy expenditure as practicable, without compromising the 'inalienable right to coolth.' We are not advocating exclusively passive design across space and time, but an enabling urban context within which buildings could be made comfortable with minimal active energy use. Climate-conscious *urban* design is at the heart of the approach.

Lest the reader conclude that an inferior form of thermal comfort is proposed, we posit that such an approach is indeed central

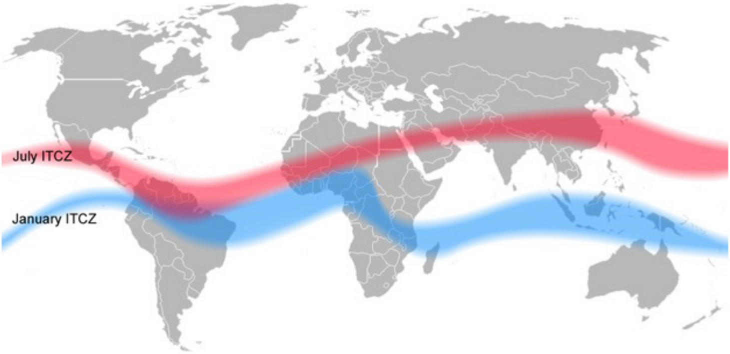


Figure 2.1. Location of intertropical convergence zone (ITCZ) in summer and winter. (Source: Mats Halldin, based on Image: ZICT en janvier.jpg, Image: ZICT en juillet.jpg, and Image: BlankMap-World.png. Licensed under Public Domain via Wikimedia Commons-http://commons.wikimedia.org/wiki/File: ITCZ_january-july.png/media\#/File:ITCZ_january-july.png)

to 'thermal pleasure' in the tropics, even in the face of a changing climate further warmed by the UHI effect. However, the prevailing notion of thermal pleasure (largely fueled by air conditioning) need to be reformulated if we are to achieve sustainable thermal comfort in the face of a changing climate made worse by the UHI effect. Such reformulation should start by acknowledging the limits of 'energy-free' comfort in the tropics.

2.1 Limitation of the 'Passive' Approach in the Urban Tropics

Tropical climate, especially the equatorial tropics, offers conditions closer to the 'ideal' temperatures year-round. For example, the annual range in maximum temperature in the equatorial coastal city of Colombo, Sri Lanka (6.9°N, 79.87°E) is 30.0–32.0°C while the range for minimum is 22.5–26.0°C. This compares favorably with the standard prescribed for indoor thermal comfort (24 ± 1°C). Yet the achievement of *thermal comfort* by passive means is remarkably difficult in the tropics. The reasons have to do with high humidity, near absence of annual variations, weak macro-level winds and higher enthalpy. High humidities make evaporative heat loss — the principal means of thermoregulation at higher temperatures — exceedingly difficult. The twice-a-year passage of the Sun directly overhead (and the associated presence of the intertropical convergence zone — ITCZ) leads to weak macro-level conditions in the tropics even though the region is very dependent on wind movement for thermoregulation. The high year-round incidence of solar radiation nearly obliterates seasonal climatic variations, thus greatly amplifying the perceived discomfort due to nearly imperceptible changes in air temperature. High incident solar radiation and the associated high humidity also lead to high enthalpy — thus high energy need — to achieve thermal comfort.

Local and global climate changes make these difficulties increasingly problematic. Prominent among these is the inadvertent climatic consequences of haphazard urbanization — characterized by the UHI effect (Oke, 1987). While the UHI effect is both a blessing and a burden in temperate climates, all aspects of urban changes to tropical climates are negative.

Given these difficulties, the achievement of thermal comfort by passive means — and at a level adequate to enhance local quality of life — is increasingly difficult in the urban tropics. It is no wonder that the tropics are turning to the air conditioner for comfort. A good example of this is Singapore, which is now said to be the 'air-conditioned nation' (cf. George, 2000). Combined with the fact that the wider tropical region is home to the largest urban transformation in contemporary human history and in the face of global and regional changes to climate, the creation of comfortable urban spaces becomes imperative, even if the mechanics of achieving it are exceedingly difficult.

The provision of cooling is wider than what a planning or an urban design remit would allow. We need a new way of being, which in turn has implications to the way tropical dwellers perceive clothing, furniture, food and indeed their bodies. While this is far too wide a subject to be covered in a single book on climate-sensitive design in the tropics, we propose three ideas that are crucial to the achievement of thermal comfort in the tropics:

1. reformulation of thermal pleasure in the tropics;
2. linking the 'in' and the 'out';
3. adaptive opportunities varied by activity patterns.

2.2 Reformulation of Thermal Pleasure in the Urban Tropics

There is anecdotal (cf. George, 2000) as well as increasingly sophisticated socio-technical evidence (Hitchings and Lee, 2008; Han *et al.*, 2009; Karyono *et al.*, 2015) that those tropical dwellers used to an air-conditioned way of life experience both physiological and cultural changes that make the toleration of tropical climates all but impossible (see. Fig. 2.2). Based on a three-year survey of 1,328 people during the summer season in Rio de Janeiro (2012–2015),[1] Drach and Krüger found that persons acclimated to an air-conditioned way of life (thermal sensation — TS (AC) in Fig. 2.2) reported nearly 2°C lower threshold of comfort (in terms of universal thermal comfort index — UTCI) (Drach *et al.*, 2015) than people used to a 'naturally ventilated' way of life (TS (no AC) in Fig. 2.2).

Such changes in thermal sensation lead to greater comfort expectation in such a manner that it is now increasingly common, as in Singapore where streets are mere extensions of the air-conditioned interiors, i.e. 'interiorized exterior spaces' (Chang and Winter, 2015: 108).

The former Prime Minister of Singapore famously stated that "it (air conditioning) changed the nature of civilization by making development possible in the tropics" (Lee, 2009). It is ironic that this was stated in the context of advancing an 'East Asian way' that is culturally and developmentally different from the West. Nevertheless, as we saw in Chapter 1, having imbibed a Western notion of comfort,

[1]Patricia R.C. Drach and Eduardo L. Krüger, "Thermal comfort in open spaces of Rio de Janeiro city: the relationship between urban density and urban heat islands." Research project supported by MCTI /CNPq /MEC/CAPES N^0 07/2011, Process number: 401387/2011-9 — Brazil.

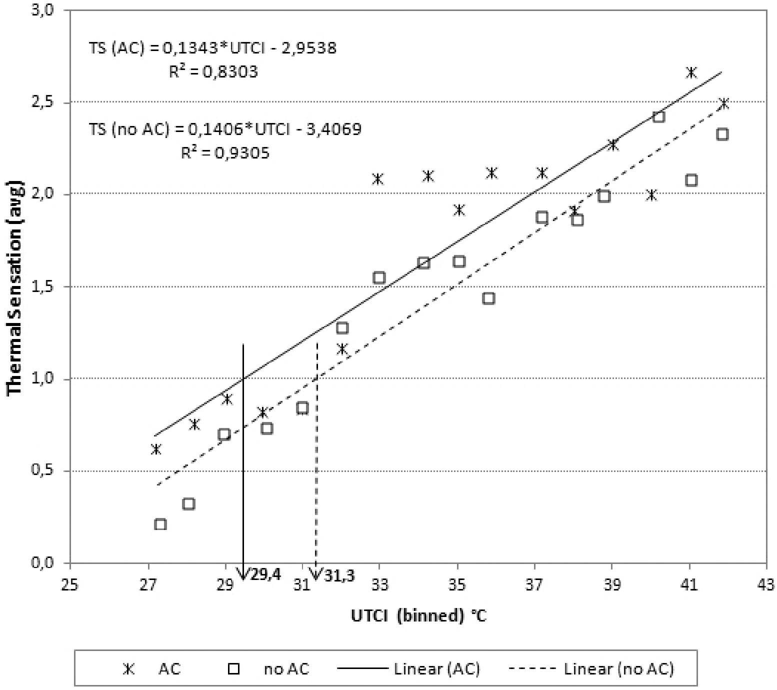


Figure 2.2. Thermal sensation of outdoor users in Rio de Janiero, Brazil, 2012–2015. Note: '*TS(AC)*' denotes survey responses from people used to non-air-conditioned way of life while '*TS(no AC)*' is from those whose lives are largely air-conditioned. Survey data come from summer of 2012, 2013, 2015 and winter 2014.

it is hard to see how Western levels of energy use and its attendant sustainability and climate change consequences could be avoided, once an air-conditioned mentality is accepted as the civilizational norm.

This calls for a reformulation of thermal pleasure in the tropics (Fig. 2.3). Thermal pleasure in a hot environment is very different to that in a cold environment: coolness is only 'skin deep' (i.e. we feel evaporative and convective cooling on the surface of the skin, as opposed to warmth, which is internal — cf. Heschong, 1979). It is also about calming the senses in a highly (almost over-) simulated environment where deep shade, vegetation and water all play a role in creating a serene and calming effect.

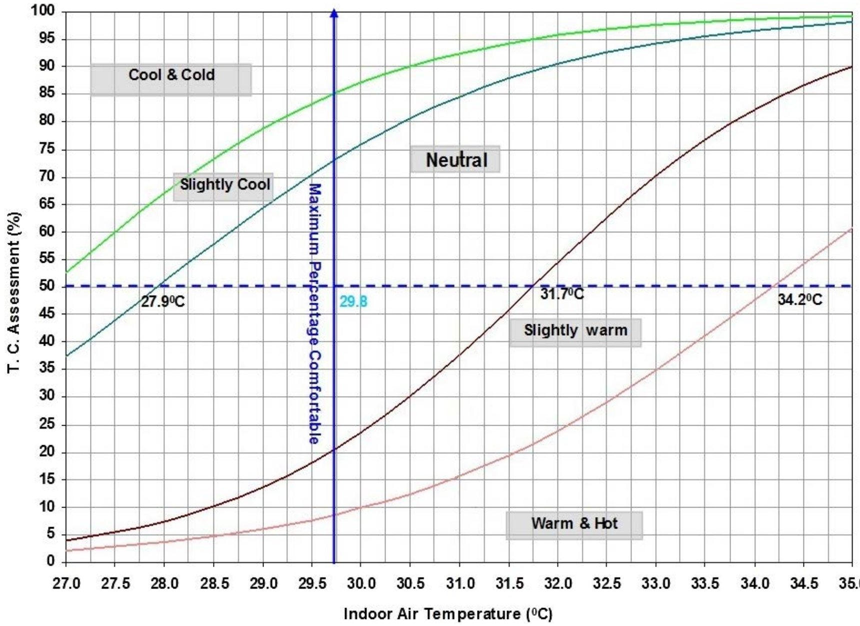


Figure 2.3. Thermal perception map for the tropics. (Source: Harimi *et al.*, 2015)

Such coolness benefits from asymmetrical thermal environment — i.e. a heightened degree of contrast (Arens *et al.*, 2006). Combining this with the fact that coolness is the preferred thermal sensation in the tropics, which is not 'neutral' but 'slightly cool' (cf. Hwang *et al.*, 2009), we have the basics of a different formulation of thermal pleasure (see Fig. 2.4) in the tropics.

At the heart of this formulation of thermal pleasure is an *urban* asymmetrical thermal environment dominated by cool spots, which enables greater enjoyment of the outdoors, thus enabling low-energy cooling in the indoors. An urban asymmetrical thermal environment could be achieved in a number of different ways, all of which aim to create climatically 'cool' urban public spaces:

- partially shaded pathways (Fig. 2.5);
- strategically placed and adequate vegetation cover (Fig. 2.6);
- water misting.

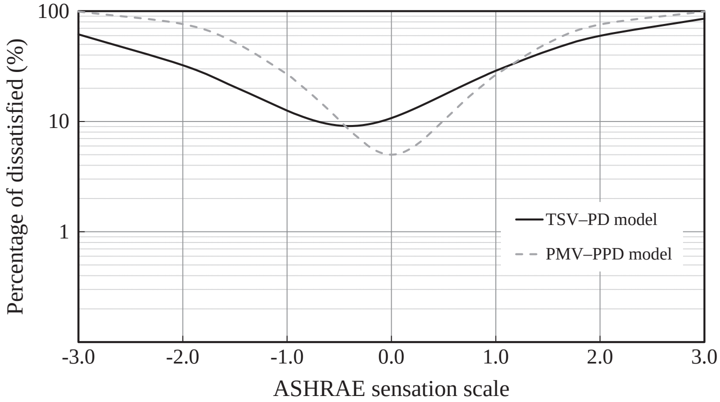


Figure 2.4. Measured thermal perception in the tropics, against predicted values of PMV/PPD. (Source: Hwang *et al.*, 2009)

Figure 2.5. Shaded pathways: arcaded street in Colombo, Sri Lanka (left) and tree-lined path in Singapore (right). (Source: Author)

Figure 2.6. Urban green cover: (left) green cover in Porto Alegre, Brazil; (right) Brisbane's South Bank Parklands. (Source: (left) http://www.boredpanda.com/porto-alegre-brazil/ (right) https://www.flickr.com/photos/tgerus/4068378356/in/photolist-7cvv9q-o95uHB-99r5jE-dehb81-8dDem4-5GguYf-99yFg5-5zm7Kf-jougfc-9abmXS-7biDFr-99vydV-7biDRR-5FAS7Z-5UoNb3-77Jiq7-7bnZFw-2V-hbdb-4CJwbx-9abnGJ-6JZmgt-9abnz1-q4Jzuo-9a8dpx-b7hJiX-mEiD6q-bxkzk-E-99nWSa-9a8cvt-fjLpXE-9abn1j-7bvSES-apEUYj-q2vdvS-9abngq-9Rx99e-bHY2Mi-eV96rv-ewrmcH-9a8cs6-pMdj3y-prCwBe-9a8dvV-5SGJaS-9a8cFV-5Cb-uvA-3AZVpa-7crF6g-8sisoZ-7cvvvo/)

2.2.1 *Shaded pathways*

The key to cool asymmetry in the public realm is to mix shade and light. This could be achieved by mandating minimum arcade cover around public buildings (it is 75% in Havana, Cuba where there is no tree cover) or regular shade intrusion on pedestrian streets (say, minimum 10 m wide shade/rain structures every 100 m — Brisbane, Australia).

2.2.2 *Vegetative cover*

Tropical cities are naturally green: Bangkok has 11.8 m^2 of green space per capita (Thaiutsa *et al.*, 2008); Singapore has 10 m^2 (Chow and Roth, 2006); Beijing has 6 m^2 (Dembner, 1993); as opposed to sub-tropical cities such as Mexico City, which has 1.9 m^2 (Deloya, 1993) and New Delhi, which has 0.12 m^2 (Kuchelmeister, 1998). The WHO-recommended minimum green cover is 9 m^2 per capita (Deloya, 1993, quoted by Thaiutsa *et al.*, 2008). Excessive rainfall

Table 2.1. Changes in perception due to being subjected to misting. (Source: Modified after Farnham *et al.*, 2015)

	Average range	Standard deviation
Thermal sensation	+ 2.71 to − 0.35	0.94
Comfort sensation	− 1.41 to + 1.82	1.03
Wettedness sensation	+ 0.82 to 1.56	1.21 to 0.86

Note:
Data show the thermal sensation, comfort sensation and 'wettedness' sensation of persons subjected to water misting. 'Average range' indicates the changes in sensation before and after being subjected to water misting. Thermal sensation was measured on a nine-level scale from extremely cold (−4) to extremely hot (+4); comfort sensation on a seven-level scale from uncomfortable (−3) to very comfortable (+3); and skin wettedness sensation on a seven-level scale from very dry (−3) to very wet (+3).

makes urban vegetation an attractive UHI mitigation option, even in high-density cities.

Although tropical cities are still relatively green, urban pressure on street trees is immense. At the same time, a cooling strategy based on urban greening can work in the tropics on account of abundant water availability and high humidity combined with year-round warm temperatures. In addition to their thermal benefits, street trees are also useful for removing pollutants from the air and for absorbing carbon dioxide, giving off oxygen, and relieving human stress. Additionally, street trees modulate run-off intensity during storms, thus helping modulate urban flood events. During periods of heat stress, there is evidence that urban greenery provides a feeling of psychological wellness (Lafortezza *et al.*, 2009).

2.2.3 *Water misting*

Evaporative cooling (water misting) has been employed as an outdoor cooling strategy for a number of years in hot, dry climates (Pearlmutter *et al.*, 1996). However, there is increasing evidence that such an approach could be successfully adapted to sub-tropical and even tropical areas experiencing severe UHI effects, to provide instant cooling in the outdoors (Farnham *et al.*, 2015).

2.3 Linking the 'In' and the 'Out'

There is clear evidence to the link between indoor thermal comfort and outdoor weather (which is now acknowledged in the so called 'adaptive approach' to thermal comfort — de Dear and Braeger, 1998). At the same time, there is great frustration at the inapplicability of universal thermal comfort norms to the specific problem faced by tropical urban dwellers (cf. Andreasi *et al.*, 2010). While the problem of ignoring the contextual factors in contemporary thermal comfort quantification is well recognized, there are other issues that need to be addressed for effective tackling of the thermal comfort problem in the urban tropics.

A critical lacuna in universal thermal comfort norms is the lack of specification of the outdoors. This is especially important in the tropics where the design norm is naturally ventilated buildings. An exclusive focus on indoor standards need to give way to a new approach that links the 'in' and 'out' (i.e. express standards in terms of percentage reduction over the contextual surroundings). It is suggested that such an approach aim to increase the difference between the 'in' and the 'out' to a level that thermal delight is enhanced by the magnitude of the difference. This will help perceive the indoor as a 'cool oasis' in a harsh and increasingly warm urban outdoors.

The achievement of thermal comfort in the tropics is about the "integration of microclimate, form and fabric of the building" (Rajapaksha and Hyde, 2012). Substantial improvement in indoor thermal comfort is possible only if efforts to do so begin at the neighborhood scale (i.e. outside the building). Indeed, the manipulation of settlement geometry, street orientation and external factors such as street trees are central to achieving thermal comfort in the tropics. Part II of this book details strategies and approaches to achieving optimal links between the two realms.

Such a link between the indoor and outdoor thermal conditions ought to reflect the purpose for which thermal comfort standards are being promulgated. Lenzuni *et al.* (2009) suggest differentiation of thermal standards along the following: the subject's thermal sensitivity, accuracy required for carrying out the task and the practicality of thermal control. We suggest a fourth: the difference between indoor and outdoor conditions to be achieved.

2.4 A Multitude of Adaptive Opportunities in the Urban Tropics

Given the year-round possibility to use the outdoors for daily living, urban thermal comfort gains greater importance in the overcrowded tropics where room occupancy rates are unhealthy (cf. Correa, 1989). A critical need is to specify outdoor thermal standards in terms of *urban activities* (Emmanuel, 1993) that facilitate comfortable movement in the outdoors, leading to higher quality of life.

> *Our own comfort zones, in any climate, can be significantly extended ... by changing our attitudes, and the values that underpin them, (and) also by making many small changes to the way we behave and the environments we occupy. (Roaf et al.*, 2015)

Such extension to the comfort zone could be greatly facilitated by the provision of adaptive opportunities that are organized around activity patterns of urban life. Emmanuel (2005) suggested four such adaptive opportunities, organized around tropical activity patterns:

1. **Shopping streets** — Create canyon-like shopping streets in large neighborhoods, where the street itself is north-/south-running, with buildings on the west being slightly taller than those on the east. Line both facades of street-facing buildings with arcades, so as to provide adequate protection from rain and sun. If north-/south-running streets are not available, create narrow shopping cul-de-sacs off major traffic arteries, thus ensuring adequate protection from traffic, while maintaining accessibility.
2. **Gathering places** — Surround urban bodies of water with a built form edged by arcades. Locate public activities along the arcade, overflowing into the commons. If north-/east-facing promenades are desired, locate the buildings in an L shape along the southern and western edges of water. If south-/west-facing arcades are desired, locate buildings along the northern edge of water, in a staggered manner. The commons in the latter case needs to be

wider. Trees need to be planted so as to provide intermittent shading to the commons. Dissuade all activities that do not directly benefit from water's edge from locating on urban waterfronts.

3. **Provisions for evening life** — Evenings are the tropics' winter (Rao, 1981). The places deserted in the heat of the day are slowly re-occupied by throngs of people as the searing afternoon sun bids farewell and darkness envelops the land. Street corners are especially attractive to be incorporated into the evening life, particularly if they intersect in a northerly and easterly orientation.
4. **Pedestrian paths and nodes** — The problem of pedestrianizing cities lies in the connections provided. Not only the provision of a safe lane but also connecting activities that people most frequently use are necessary. Therefore, establish a network of pedestrian links independent of the city street network. Paths within city blocks could be the primary carriers of cool air (say from a pond). Wherever the pedestrian path crosses the vehicular path, establish a place to pause. At places, let the pedestrian path merge with the street network, especially if the street is north-/south-running. Let such streets be very narrow with buildings on both sides providing shade to the entire street. Line the rest of the path with trees, or alternatively, cover it with a light roof.

A useful threshold to thermal acceptability in the outdoors is the skin wettedness (w). w is dependent on metabolic rate (m) and, based on a long pedigree of research on skin wettedness and thermal comfort, Havenith *et al.* (2002) suggested the following thermal comfort requirement:

$$w < 0.0012M + 0.15. \tag{2.1}$$

While w is commonly expressed in terms of regulatory sweat evaporation rate and the maximal evaporation rate possible in ambient climate, a more useful relationship in terms of metabolic rate, atmospheric pressure (p_a) and clothing vapor resistance (R_e) is given by Havenith *et al.* (2002):

$$w = \frac{0.42(M - 58)R_e}{5770 - 7.2M - p_a}. \tag{2.2}$$

Furthermore, the thermal comfort limitation of w is usually said to be 0.3 (Havenith *et al.*, 2002), which together with Eqs. 2.1 or 2.2 could be used to determine design options for each of the four activity patterns listed above.

Finally, there is a need to acknowledge the urban changes to climate in any future thermal comfort standards for the tropics. Given the lack of resources and the sheer scale and rate of urbanization, it is likely the outdoor climatic conditions will be subject to intense heat island pressures in the coming decades. Outdoor thermal comfort standards need to reflect the urban changes to climate in a dynamic manner. Precedence for such an approach was recently suggested by Kwok and Rajkovich (2010), who attempt to link thermal comfort standards to reflect global climate changes.

2.5 Final Word

> *(T)he historical role of architecture [as the] controller of climatic environment ... influences the fate of nations ... if this historical analysis is correct, it is time for architects to learn to master hot climates to restore the "balance of power". (O.H. Koenigsberger, 'Lecture on the Importance of Climate,' quoted by Chang and Winter, 2015)*

Once life is organized around the air conditioner and the air-conditioned life becomes the norm, it becomes exceedingly difficult to actively seek other ways of achieving comfort. It is not just that people get accustomed to constant coolth but also the "ways of puncturing practice" (Hitchings, 2011) are hard to come by in an urban lifestyle completely mechanically conditioned. In a study of London office workers' reason for rarely venturing out, even when it was pleasant, Hitchings (2011) characterized their behavior as "cultivated indifference to everyday outdoors" rather than an addiction to air conditioning. The provision of adaptive opportunities could increase the use of urban outdoors, thus reducing the thermal expectation from the indoors.

Urban development is piece-meal and occurs over an extended period of time, under the influence of several actors and across several urban administrations. A convincing narrative is therefore needed to sustain the growth in a manner conducive to positive quality of life. The amelioration of UHI effects provides such an approach. A critical metric to ensure continuity of vision is to use a new yardstick based on climate change potential, termed as the urban climate change potential (UCCP) (Emmanuel, 2009). The UCCP is the measure of the likely local climate effects of a proposed urban physical developmental action. In so far as is practicable, the numerous social, economic and environmental measures needed for sustainable urban development should be converted to physical climatic effects and expressed in terms of UCCP. The UCCP offers not only an integrated metric but also leads to something easily understood by all stakeholders in an environment already too hot for comfort. This has the advantage of being applicable to physical infrastructure development at all stages, be it building construction, transportation development, urban green enhancement, water-front development or urban regeneration. The next section of the book will highlight key strategies to operationalize climate-sensitive planning and design actions in the tropics:

- air ventilation assessment (AVA) being mandatory for all neighborhood and city-wide planning efforts;
- urban densification with the aim of increasing street-level shading being the principal planning goal;
- contiguous shading of public realm driving urban regeneration efforts; and
- street-level vegetation being part of the design template.

Since climate change agenda is now at the center of public consciousness, amelioration of UHI provides a local narrative within which strategies for the enhancement of urban quality of life can find acceptance and even active support. A political difficulty with action against global climate change is the inability to see results in the here and now. This is further confounded by weak science in terms of cause and effect. Tackling urban climate change on the other hand offers immediate and tangible benefits, since the negative consequences of haphazard urbanization are plain to see. Herein lies a possibility to marry both adaptive and mitigatory actions at the local scale, where the benefits are immediate and local (and therefore politically feasible), while contributing over an extended period of time to the global efforts at adapting to climate change. Rapidly growing tropical cities need to play this role now before the local climate turns irreversibly intolerable. In the face of global climate change, this will also give tropical cities a leg up in the two-way knowledge transfer (between the developed and developing worlds) of experiential awareness and local action for living in a warming world.

References

Andreasi, W.A., Lamberts, R., Cândido, C. (2010). Thermal acceptability assessment in buildings located in hot and humid regions in Brazil, *Building and Environment*, **45**, 1225–1232.

Arens, E., Zhang, H. and Huizenga, C. (2006). Partial- and whole-body thermal sensation and comfort — Part II: Non-uniform environmental conditions, *Journal of Thermal Biology*, **31**(1–2), 60–66.

Chang, J.-H. and Winter, T. (2015). Thermal modernity and architecture, *The Journal of Architecture*, **20**(1), 92–121.

Chow, W.T.L. and Roth, M. (2006). Temporal dynamics of the urban heat island of Singapore, *International Journal of Climatology*, **26**, 2243–2260.

Correa, C. (1989). *The New Landscape: Urbanization in the Third World*, London: Butterworth Architecture.

Deloya, M.C. (1993). Urban forestry activities in Mexico, *Unasylva*, **173**, 28–32.

Dembner, S.A. (1993). Urban forestry in Beijing, *Unasylva*, **173**, 13–18.

Drach, P., Krüger, E. and Drach, H. (2015). "Outdoor comfort study in downtown Rio de Janeiro, Brazil", 9th International Conference on Urban Climate (ICUC9) jointly with 12th Symposium on the Urban Environment, 20–24 July 2015, Toulouse, France.

Emmanuel, R. (1993) A hypothetical 'shadow umbrella' for thermal comfort enhancement in the Equatorial urban outdoors, *Architectural Science Review*, **36**, 173–184.

Emmanuel, R. (2005). *An Urban Approach to Climate Sensitive Design: Strategies for the Tropics*, E&FN Spon Press, London, UK.

Emmanuel, R. (2009) "Sustainable urbanity and urban climate change: Amelioration of UHI's as a quality-of-life agenda for tropical megacities", 7$^{\text{th}}$ International Conference on Urban Climate (ICUC7), 29 Jun–3 Jul 2009, Yokohama, Japan, http://www.ide.titech.ac.jp/~icuc7/extended_abstracts/pdf/384615-1-090516001218-003.pdf.

Farnham, C., Emura, K. and Mizuno, T. (2015). Evaluation of cooling effects: outdoor water mist fan, *Building Research & Information*, **43**(3), 334–345.

George, C. (2000). *Singapore, the Air-Conditioned Nation: Essays on the Politics of Comfort and Control, 1990–2000*, Landmark Books, Singapore.

Han, J., Yang, W., Zhou, J. *et al.* (2009). A comparative analysis of urban and rural residential thermal comfort under natural ventilation environment, *Energy and Buildings*, **41**, 139–145.

Havenith, G., Holmér, I. and Parsons, K. (2002). Personal factors in thermal comfort assessment: clothing properties and metabolic heat production, *Energy and Buildings*, **34**(6), 581–591.

Harimi, D., Ming, C.C. and Kumaresan, S. (2015). A generalized thermal perception approach for indoor thermal comfort assessment in the humid tropics of Malaysia, *Energy and Buildings*, **88**, 276–287.

Heschong, L. (1979). *Thermal Delight in Architecture*, Cambridge, MA.: MIT Press.

Hitchings, R. (2011). Researching air-conditioning addiction and ways of puncturing practice: professional office workers and the decision to go outside, *Environment and Planning A*, **43**(11), 2836–2856.

Hitchings, R. and Lee, S.-J. (2008). Air conditioning and the material culture of routine human encasement: the case of young people in Singapore, *Journal of Material Culture*, **13**, 251–265.

Hwang, R.-L., Cheng, M.-J., Lin, T.-P. *et al.* (2009). Thermal perceptions, general adaptation methods and occupant's idea about the trade-off between thermal comfort and energy saving in hot–humid regions, *Building and Environment*, **44**(6), 1128–1134.

Karyono, T.H., Heryanto, S. and Faridah, I. (2015). Air conditioning and the neutral temperature of the Indonesian university students, *Architectural Science Review*, **58**(2), 174–183.

Kuchelmeister, G. (1998). "Urban forestry in the Asia-Pacific Region — situation and prospects", Document APFSOS/WP/44, FAO, Rome/Bangkok.

Kwok, A.G., Rajkovich, N.B. (2010). Addressing climate change in comfort standards, *Building and Environment*, **45**, 18–22.

Lafortezza, R., Carrus, G., Sanesi, G. *et al.* (2009). Benefits and well-being perceived by people visiting green spaces in periods of heat stress, *Urban Forestry and Urban Greening*, **8**, 97–108.

Lee, K.Y. (2009). The East Asian way — with air conditioning, *New Perspectives Quarterly*, **26**(4), 111–120, http://www.digitalnpq.org/archive/2009_fall_2010_winter/16_yew.html.

Lenzuni, P., Freda, D., Del Gaudio, M. (2009). Classification of thermal environments for comfort assessment, *Annals of Occupational Hygiene*, **53**, 325–332.

Oke, T.R. (1987). *Boundary Layer Climates*, 2nd ed., London: Routledge.

Pearlmutter, D., Erell, E., Etzion, Y. *et al.* (1996). Refining the use of evaporation in an experimental downdraft cool tower, *Energy and Buildings*, **23**, 191–197.

Rajapaksha, U. and Hyde, R. (2012). Barriers to and opportunities for advanced passive cooling in sub-tropical climates, *Architectural Science Review*, **55**(1), 49–60.

Roaf, S., Nicol, F. and Rijal H. (2015). Designing for comfort at high temperatures, *Architectural Science Review*, **58**(1), 35–38.

Thaiutsa, B., Puangchit, L., Kjelgren, R. *et al.* (2008). Urban green space, street tree and heritage large tree assessment in Bangkok, Thailand, *Urban Forestry and Urban Greening*, **7**, 219–229.

This page intentionally left blank

Chapter 3

Management of shading and public places

Tzu-Ping Lin

3.1 Introduction

In Taiwan — a hot-humid region consisting of sub-tropical and tropical climates where the Tropic of Cancer (latitude 23.5°N) runs through, — local people tend to look for shading when they are engaged in outdoor or semi-outdoor activities during the day (Fig. 3.1). While walking in the outdoor open areas, people often use umbrellas to shield against solar radiation. When motorcycle riders stop for a red light, they also tend to stop under street trees which offer shade. When walking on the overpass in dense business areas, pedestrians are inclined to walk in sunless areas. If the bus stop roof cannot shade the seating area, people would rather stand in the shade waiting for the bus. These behaviors reveal several important relevant issues, including:

(1) thermal comfort of people in the tropics;
(2) the influence of shading on thermal environment; and
(3) the correlation between shading and users' behavior.

First, in order to understand this phenomenon, the thermal comfort of (sub-)tropical people should be discussed. Thermal comfort refers to the overall subjective perceptions about air temperature (T_a), air humidity, wind speed and mean radiant temperature (T_{mrt}) under the known conditions of clothing and metabolism. The thermal comfort is closely related to local climate, as well as the

Figure 3.1. (Sub-)tropical people tend to stay in the shade in outdoor spaces. (Source: Photos by Tzu-Ping Lin, Tun-Pin Chen, and Yam-Ting Lin)

users' preferences, expectations, personal habits, perceived control and cultural background, which are collectively known as thermal adaptation (McIntyre, 1980; Paciuk, 1990; Malama *et al.*, 1998; Karyono, 2000; Brager *et al.*, 2004; Feriadi and Wong, 2004; Hwang and Lin, 2007; Lin and Matzarakis, 2008). Hence, by understanding (sub-)tropical people's preference for specific climatic factors, the key factors influencing their thermal comfort conditions can be identified. Section 3.2 of this chapter thus probes into local users' thermal comfort characteristics based on the existing database of thermal comfort investigation.

Furthermore, in terms of physical mechanism, determining which aspects of the thermal environment are influenced by shading deserves research. Section 3.3 uses Taiwan as an example to discuss the influence of shading levels and shading material on the thermal environment and thermal comfort, in order to consider and conclude the design details of shading.

Finally, as the ultimate goal of the designers is to improve the satisfaction and utilization rate of outdoor space, Sec. 3.4 discusses the ratio of shading to space and its influence on users' behavior. The correlation between space utilization rate and thermal environment under different shading characteristics is discussed based on three surveys in Taiwan's parks and squares with various shading patterns.

The discussions can clarify the benefits of the shading factor on mitigating the thermal environment and improving thermal comfort. The findings can provide designers with important information for outdoor spaces in tropical regions, so as to create comfortable and satisfactory outdoor spaces for (sub-)tropical people.

3.2 Thermal Comfort and Preference

3.2.1 *Thermal comfort range*

In Taiwan, Hwang and Lin (2007) conducted a thermal comfort survey as part of the FIOT project (Field Investigation of Outdoor Thermal Comfort), in which physical microclimatic measurements were made concurrently with questionnaire surveys in a variety of indoor, semi-outdoor and outdoor spaces in central Taiwan, including Taichung, Yunlin and Chiayi. A total of 8,077 sets of data were collected from the winter of 2004 to the summer of 2005. A total of 1,644 interviews in the outdoors from the FIOT database are analyzed in this section. Details on the methods related to the physical environment measurement and questionnaire survey may refer to previous studies (Hwang and Lin, 2007; Lin and Matzarakis, 2008; Lin *et al.*, 2011). Furthermore, 2,071 interviews in Weather Perception and Preference Survey (WEPPS) project were conducted for more complete and diverse questionnaires on thermal comfort from 2011 to 2014 in tropical and subtropical Taiwan (Lin *et al.*, 2015)

Figure 3.2 shows the percentages of unacceptability to each 1°C physiologically equivalent temperature (PET) interval. The 80% acceptability limits are the intersections of the fitted curve and the

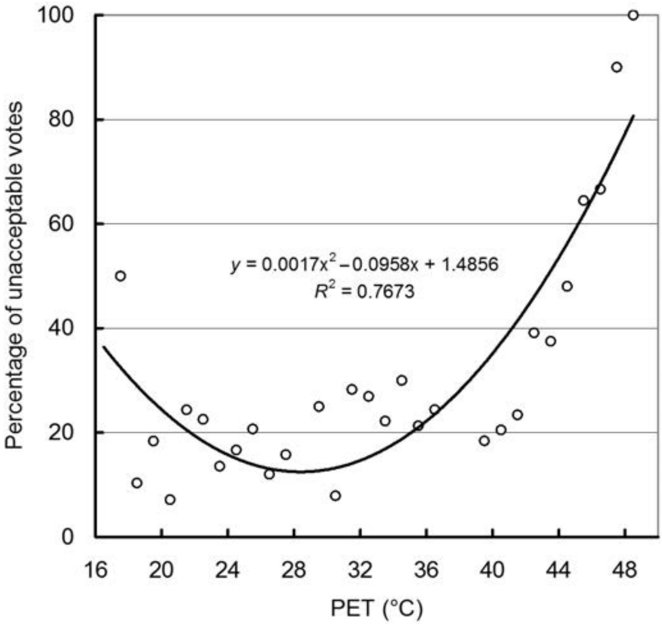


Figure 3.2. Thermal comfort range for outdoor environments in Taiwan. (Source: Lin and Matzarakis, 2008)

20% unacceptability line, which is 21.6–35.4°C. In order to focus precisely on the comfort range and to minimize the data range, the 88% acceptability limit was chosen for 'neutral', i.e. 26–30°C PET (Lin and Matzarakis, 2008). The comfort range for Taiwanese is higher than those for Western/Middle Europeans, i.e. 18–22°C PET (Matzarakis and Mayer, 1996). The results indicated that people in hot-humid areas may tolerate higher thermal conditions.

However, (sub-)tropical area people accepting (or tolerating) higher temperature does not mean they prefer higher thermal conditions. Lin (2009) indicated that thermal comfort can also be defined as a condition in which individuals prefer neither warmer nor cooler temperatures (Fanger, 1973), i.e. the preferred temperature. While neutral temperature is the temperature at which people feel comfortable, preferred temperature is the temperature people want. Probit analysis (Ballantyne *et al.*, 1977) is applied to calculate preferred temperature based on preference votes, i.e. votes for warmer or cooler temperatures.

According to a previous method (de Dear and Fountain, 1994), the neutral temperatures for the cool and hot season are 23.7°C and 25.6°C PET, respectively, while the preferred temperatures in the cool and hot seasons were 23°C and 24.5°C PET, which are 0.7°C and 1.1°C lower than the neutral temperatures obtained in their study. In the hot season, people may feel that 25.6°C is comfortable, but would rather that T_a decreases to 24.5°C. The difference between what they feel and what they prefer is 1.1°C. This comparative result demonstrates the impact of expectations concerning thermal comfort, indicating that the expectation for a low T_a in the hot season is stronger than that in the cool season.

This analytical finding also proves that people yearn for cool conditions in a hot climate, a finding consistent with the assumption by McIntyre (1980). In contrast, people in temperate regions may prefer higher thermal conditions than the neutral condition. Therefore, for people in tropical areas the cooler thermal condition should be offered to fit their expectations.

3.2.2 *Preference for less sun*

This section discusses the relation between people's overall thermal sensation and their perception regarding the sun from the FIOT data. Simple linear regression analyses were performed to determine the strength of the relationship between sun sensation vote and thermal sensation vote. Figure 3.3 shows the relationship between sun sensation votes (−3 to +3 representing too weak to too strong) and thermal sensation votes (TSV, −3 to +3 representing too cold to too hot). The results indicate that respondents tend to feel warm when they feel the sun is too strong. Conversely, they feel cool when they feel the sun is too weak.

Figure 3.4 illustrates the various stack bar charts of percentage distribution based on the three point scales of the sun preference vote in each category of the TSV scale. Occupants who experienced thermal discomfort (i.e. who voted for extreme values outside the

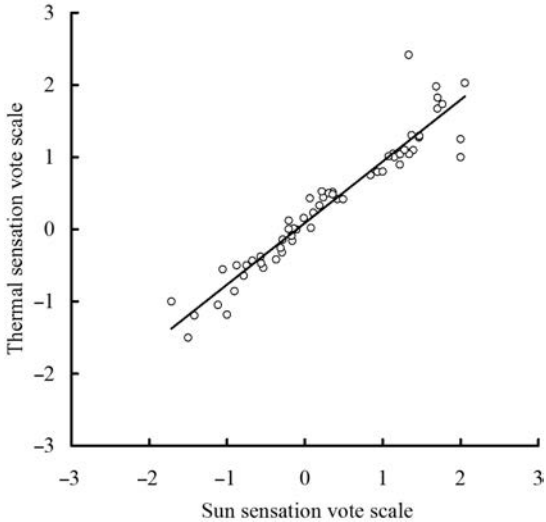


Figure 3.3. The relationship between sun sensation votes and mean thermal sensation votes. (Source: Hwang and Lin, 2007)

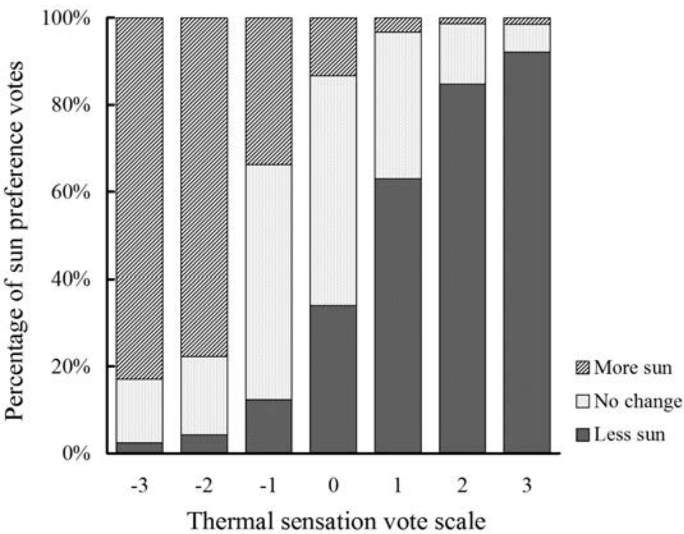


Figure 3.4. Percentage of sun preference votes for each TSV scale in semi-outdoor and outdoor environments. (Source: Hwang and Lin, 2007)

central three categories of TSV) in the outdoors would prefer to change the current global radiation conditions.

Figure 3.4 shows that the sun preference percentage distributions in the 'warmer-than-neutral' region are remarkable, with percentages of 'less sun' votes exceeding 80% and 90%, which corresponds to +2 and +3 on the TSV scale. Notably, approximately 80% of votes are located in the 'more sun' scale, which corresponds to −3 and −2 on the TSV scale. 'Less sun' votes in the 'cooler-than-neutral' region and 'more-sun' votes in the 'warmer-than-neutral' region are comparatively rare.

These vote distributions reflect that respondents have stronger expectations regarding changing global radiation. The above findings not only provide information regarding individual preferences in relation to improving the comfort of their surrounding environment, but also provide designers and engineers with methods of designing a comfortable outdoor environment.

Lin *et al.* (2011) applied the FIOT data in seeking to clarify whether people's preferences are determined by the combination of physical microclimatic parameters and psychological factors. To explore this issue within the FIOT database, all datasets were sorted into bins, each corresponding to a 1°C standard effective temperature (SET*) interval; Figure 3.5 plots the subjects' preference for sunshine intensity versus actual measurements of the mean radiant temperature (T_{mrt}) for each SET* bin in the hot season. As SET* and T_{mrt} increase, the percentage of those who 'prefer stronger sunshine' declines; therefore, the percentage of those who 'prefer weaker sunshine' increases. It reveals that people prefer the reduction of the solar radiation to maintain their thermal comfort in hot season. A similar result can be also found in the WEPPS project data (Lin *et al.*, 2015).

3.3 The Effect of Shading on Thermal Environment

The analysis result of thermal comfort and thermal preference in Sec. 3.2 shows that (sub-)tropical people have high acceptance (tolerance) for high temperature, but they still expect a low-thermal

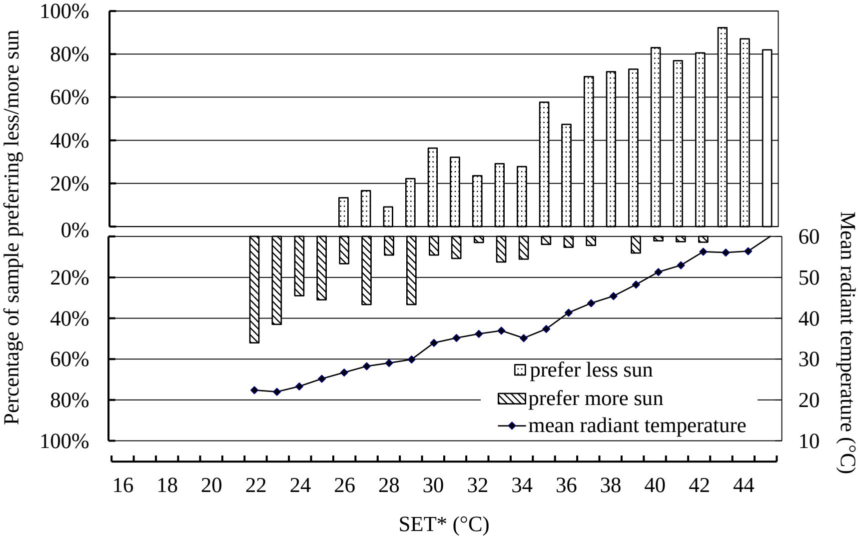


Figure 3.5. Subjects' preference for sunshine vs. T_{mrt} for each SET* bin in the hot season. (Source: Lin *et al.*, 2011)

environment. Concerning people's perception and preferences on sun, the results indicated that people's perception of the sun influences their feeling of the overall thermal environment directly. When people feel an intense sun, they evaluate the overall thermal environment as very hot. When they feel hot, they hope for less sun. Furthermore, the thermal indices increase obviously with T_{mrt}, and a higher percentage of people expect less sun.

This suggests that in hot seasons, reducing the mean radiant temperature of outdoor environments can mitigate (sub-)tropical people's discomfort level and enhance their satisfaction with the thermal environment. Concerning the reduction of T_{mrt}, the theory of T_{mrt} is explained as follows.

T_{mrt} combines the thermal effect of all short- and long-wave radiation fluxes reaching the body into one temperature-unit value (Fanger, 1972; VDI, 1998; Höppe, 1999; Matzarakis *et al.*, 2007; Kántor *et al.*, 2013). It is defined as the uniform temperature of an imaginary black-radiant enclosure in which the body would exchange the same energy via radiation as in the real environment (ASHRAE, 2001).

The mentioned radiation includes short-wave radiation (direct, diffuse and reflected radiation) and long-wave radiation (thermal radiation from the sky and emitted from the surfaces) (Kántor and Unger, 2011; Höppe, 1999; Matzarakis *et al.*, 2007; Kántor *et al.*, 2013). During the daytime period, the direct solar radiation is the most contributive factor for T_{mrt} in open areas.

Therefore, shading is an important factor and contributes to T_{mrt} because it blocks sunlight, mitigating the thermal discomfort that is caused by short-wave radiation. Furthermore, shadows on the ground decrease surface temperatures, reducing long-wave radiation (Matzarakis *et al.*, 1999; Emmanuel *et al.*, 2007; Lin *et al.*, 2010; Hwang *et al.*, 2011).

Since shading can block direct solar radiation, numerous studies have examined the effects of shading on outdoor thermal environments. For instance, previous studies (Shashua-Bar *et al.*, 2010; Emmanuel and Johansson, 2006; Johansson, 2006; Johansson and Emmanuel, 2006; Emmanuel *et al.*, 2007) quantified the height/width (H/W) ratio of urban streets to assess shading levels, whereas the sky view factor (SVF) was used in other studies as representative of shading levels (Dimoudi and Nikolopoulou, 2003; Giridharan *et al.*, 2005; 2007; Hamdi and Schayes, 2007; Ketterer and Matzarakis, 2014). The SVF can be defined as the percentage of free sky at specific locations, with values between 0 and 1 representing totally obstructed and totally free spaces, respectively (Oke, 1981; 1987). These studies proved that higher shading levels (i.e. higher H/W ratio or lower SVF value) contribute to lower T_{mrt} in outdoor environments.

In order to realize each characteristic of shading on the thermal environment and thermal comfort, the following cases in Taiwan are the focus of explanations.

3.3.1 *Shading levels and T_{mrt}*

In order to prove the importance of shading in outdoor spaces, this section uses a study by Lin *et al.* (2006) focused on several bus stops. Bus shelters are semi-outdoor spaces with shelter provided in the

Figure 3.6. Fisheye photos and appearance of the selected measured bus shelters. (Source: revised from Lin *et al.*, 2006)

form of a roof. The thermal comfort of bus shelters is as important as that of buses themselves in improving the quality of the experience of bus travel. This study sampled five different types of bus shelter together with an unsheltered outdoor location for comparison. The instruments were set up on the ground in the center of the bus shelter. The experiment locations were located close together to facilitate the comparison.

We selected three locations as example — namely, locations A and E for two bus stops with different shading level and location F in an open area for comparison. The SVF displayed in Fig. 3.6 indicates the proportion of the total sky area above the bus shelter that is covered, and thus indicates the extent of shelter provided by the roof. The SVF values are calculated by the model, and determined by the imported fisheye photo (Fig. 3.6). Location A clearly has the highest SVF value (0.586) and demonstrates the worst sheltered performance. Meanwhile, location E has a lower SVF value of 0.212.

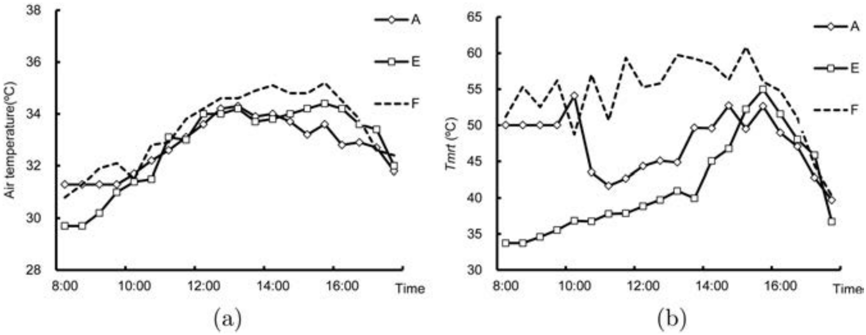


Figure 3.7. Measure air temperature (a) and T_{mrt} (b) for each bus shelter. (Source: revised from Lin *et al.*, 2006)

Figure 3.7(a) shows that the two locations under the bus shelter share similar variations in air temperature. Location F has a slightly higher T_a than those under the shelters. Meanwhile, the T_{mrt} variations in Fig. 3.7(b) demonstrate a significant temperature difference between two bus shelters. Most of the time the *Tmrt* in location A are higher than in location E, especially from 8:00 to 11:00, reaching 15°C difference in T_{mrt}. This is because there are no obstacles in the east side of the upper sky in location A and the incident solar radiation is not blocked, contributing a higher T_{mrt} in location A than in location E. After 16:00, the upper sky in both locations A and E is not blocked; therefore, the two locations have similar T_{mrt} in the late afternoon.

The main reason that SVF affects thermal comfort is that the shelter provides protection against direct solar radiation, reducing the duration hours of exposure to the sun and reducing the radiation exposure of bus shelter occupants. To explain this phenomenon, the potential sun duration hours due to the shading of a specific location is simulated in the RayMan model (Matzarakis *et al.*, 2007; 2010) by importing the fisheye photos. The sun duration ratio, which is defined as potential sun duration hours over the maximum sun duration hours (as open sky condition), are also calculated and plotted in Fig. 3.8. It indicates that location E with better shading

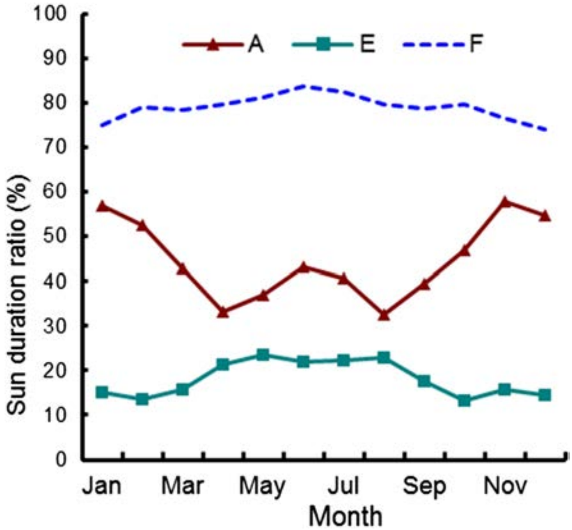


Figure 3.8. Variation of sun duration ratio of each bus shelter. (Source: revised from Lin *et al.*, 2006)

has shorter mean possible sun duration and sun duration ratio than barely shaded location A.

This result indicates that SVF is one of the initial factors in determining the solar radiation and thermal environment; the local sun orbit should be considered for creating well sheltered spaces for comfortable semi-outdoor environments.

The results indicate that bus shelters with lower SVF (or better sheltered) can help reduce direct solar radiation and provide comfortable spaces for the local weather and the preferences of occupants in semi-outdoor environments in Taiwan. To design bus shelters passively, spaces should have good shelter and lower SVF values, and designers should consider local patterns of sunlight and simulate these patterns over the entire year.

3.3.2 *Shading levels and long-term thermal comfort*

Shading not only affects the thermal environment, but also determines the long-term thermal comfort. Hwang *et al.* (2011) have focused on six locations characterized by different shading levels

A (SVF = 0.24)

E (SVF = 0.56)

F (SVF = 0.62)

Figure 3.9. Fisheye and street photographs and SVF of each measurement location. (Source: revised from Hwang *et al.*, 2011)

on traditional streets of Huwei Township. Among the six measurement locations, SVF ranges from highly shaded — point A (SVF = 0.24) — to the barely shaded — point F (SVF = 0.62) — as shown in Fig. 3.9. Field experiments on the thermal environment were applied to calibrate the RayMan model (Matzarakis *et al.*, 2007; 2010). Furthermore, long-term thermal comfort is predicted by applying meteorological data for a 10-year period.

According to the assumptions and prediction method described in Hwang *et al.* (2011), meteorological data were corrected and

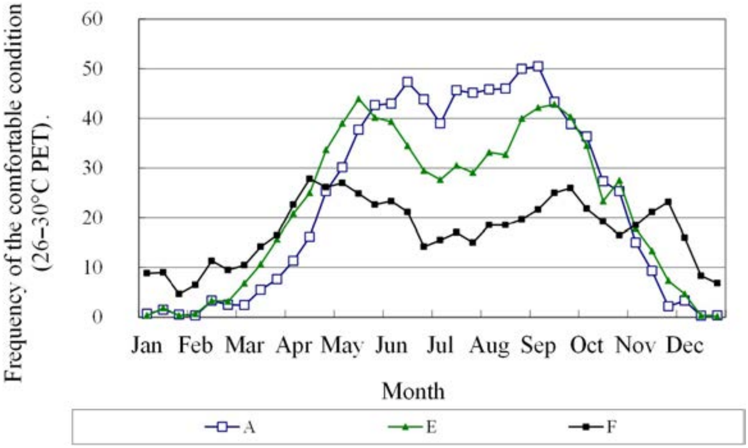


Figure 3.10. Predicted frequencies of thermal comfort condition for 08:00–18:00, 2000–2009. (Source: revised from Hwang *et al.*, 2011)

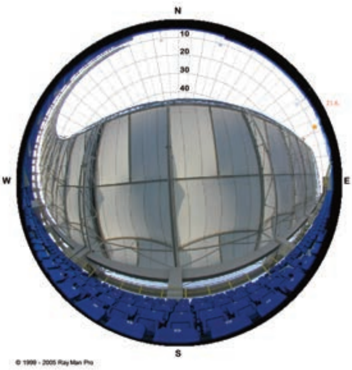
imported into the model to derive hourly PET over the last 10 years (2000–2009). Figure 3.10 shows the frequency of the comfortable condition, i.e. $F_{26<PET<30}$. The $F_{26<PET<30}$ of the slightly shaded location (F), was 10–30% all year, while that of the highly shaded location (A), was high in summer and low in winter. This is because the warm conditions at these highly shaded locations seldom occurred during summer and cool conditions were extremely frequent during winter; therefore, the thermal comfort is high in summer and low in winter at highly shaded locations. Therefore, different shading levels contribute to the variation in the thermal perception distribution.

3.3.3 *Shading material and T_{mrt}*

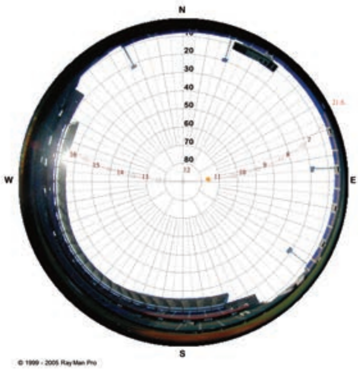
Besides the shading levels discussed in the previous sections, the shading material is closely correlated to T_{mrt}. Lin and Hsu (2007) measured and analyzed the thermal environment of Yunlin baseball field in central Taiwan, where a membrane structure is used as the roof shading material for the infield seating area of the baseball field, and the outfield seating area is unshaded, as shown in Fig. 3.11.

The T_{mrt} distribution of the two places is shown in Fig. 3.12. Generally, the T_{mrt} of a place with a high shading ratio should be

(a)



(b)



(c)

Figure 3.11. Area with membrane structure as roof construction in the baseball field (a), and infield seat under membrane structure (b), open unshaded outfield seat (c). (Source: revised from Lin and Hsu, 2007)

higher than that of an open area. However, Fig. 3.12 shows that during some time intervals, the T_{mrt} of infield seats under the membrane is even higher than that of the unshaded outfield seats. The reason may involve short-wave and long-wave radiation quantities. First, as the membrane is semi-transparent material with limited resistance to short-wave solar radiation, some of the solar radiation penetrates through the membrane structure to the seats. In addition, when the

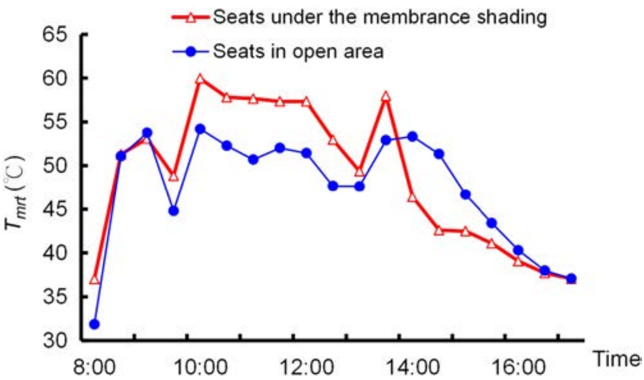


Figure 3.12. T_{mrt} variation of the two measured locations. (Source: revised from Lin and Hsu, 2007)

membrane material is heated in the sun, the upward material surface temperature rises; as the material is very thin and has less thermal insulation, the downward material surface temperature also rises, dispersed downward as long-wave radiation. The T_{mrt} of seats under the membrane increases to even higher levels than the unshaded outfield seats during some periods. This suggests that the roof material also has significant influence on the degree of comfort.

In tropical regions, the roofs of many artificial rest or waiting spaces are made of transparent materials (e.g. glass, membrane, semi-transparent PVC) or material with poor thermal insulating property (e.g. thin metal plate). From the aspect of thermal comfort, the shielding effect is rather limited, and the high surface temperature is likely to increase the radiant quantity, resulting in discomfort. Therefore, it is necessary to carefully select non-transparent and well insulating materials, so as to meet the requirement for outdoor thermal comfort.

3.4 Effect of Shading on Space Usage

Levels of outdoor shading influence outdoor thermal environments and human thermal comfort, thereby indirectly affecting the utilization of space.

Previous studies have discussed the relationship between outdoor thermal environments and the utilization of outdoor space in temperate climate zones, such as the UK (Nikolopoulou *et al.*, 2001) and Sweden (Thorsson *et al.*, 2004; Eliasson *et al.*, 2007). Their results indicated that the number of users increase in accordance with preferable thermal indices in the environment both in summer and winter. However, this phenomenon may change in (sub-)tropical regions, especially when the shading issue is involved. This section will discuss three field surveys in Taiwan that explore this issue. In these studies, the thermal parameters are measured and the numbers of people attending the park or square are counted simultaneously. For the details of the methods applied in these studies, one may refer to the corresponding references (Lin, 2009; Lin *et al.*, 2012; 2013).

3.4.1 *Unshaded square*

The first study area is a barely shaded open square in front of the National Taiwan Museum of Fine Arts (NTMOFA) in Taichung City in central Taiwan, located at 120° 40′ E, 24° 08′ N (Lin, 2009). Analytical results indicate that the PET are strongly and positively correlated with the number of people in the square in winter, while a negative correlation was found in the hot season. The results indicate that the thermal environment significantly influences square use, demonstrating that a cool temperature in the hot season and a warm temperature in the cool season attract residents to the square. Notably, T_a has also been compared to numbers of people in the square, but derives a lower coefficient of determination (R^2) than PET. Comparison results can be explained by changes in short- and long-wave radiation fluxes during hot days that affect the T_{mrt}, which indirectly reflects changes in PET values. Therefore, compared to T_a, which cannot reflect radiation levels, PET are better able to explain changes in the number of people visiting the square during the hot season when solar radiation is strongest.

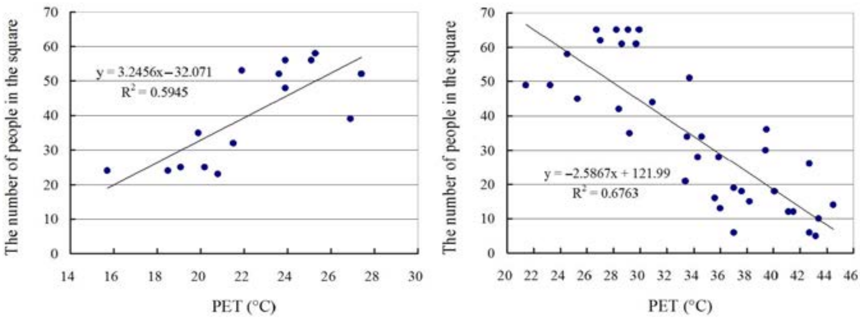


Figure 3.13. The number of people in the square in relation to PET in the (a) cool and (b) hot season. (Source: Lin, 2009)

3.4.2 *Highly shaded park*

The second study area is a highly shaded park (Tongsin Park) in Huwei Township, Yunlin County, in central Taiwan, located at 23° 43′ N and 120° 26′ E (Lin *et al.*, 2012). In order to discuss the correlation between thermal environment and attendance in various shading levels, they define the attendance density (AD, people/m^2), which is the ratio of observed number of those in attendance (people) to the size of area (m^2); this represents the number of people attracted to a particular area. For the levels of shading in each area, the averaged SVF (SVFa) are calculated in each 1 × 1 m grid by the SkyHelios model (Matzarakis and Matuschek, 2011), instead of the traditional single-point SVF.

Figure 3.14 shows the relationship between SVFa and AD; the correlation is exponential with $R^2 = 0.84$. A decline in SVFa results in a significant increase of AD. In other words, when the average shading level of a specific area is comparatively higher, the park attendance is also higher.

3.4.3 *Multiple-shaded park*

The third study area is a multiple-shading-levels park (Chung Cheng Park) in Chiayi City, in southern Taiwan, located at 23° 29′ E and 120° 27′ N (Lin *et al.*, 2013). This section will focus on two locations in the park, which are shaded by ample vegetation and buildings, with activities mainly involving quiet sitting, resting and chatting.

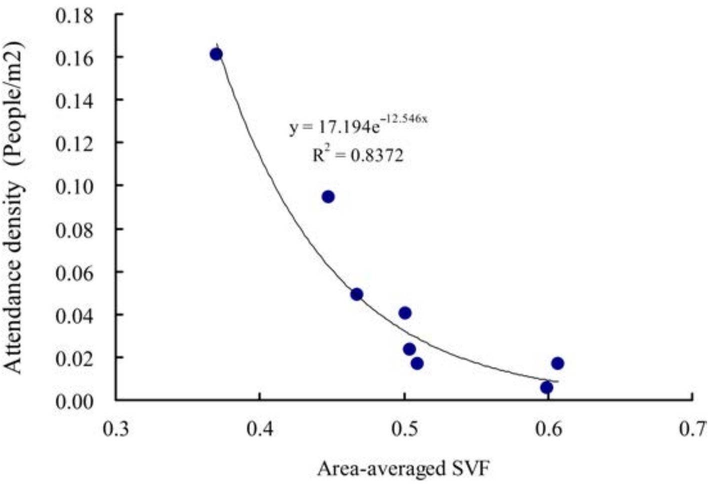


Figure 3.14. The correlation of averaged SVF and attendance density in each region. (Source: Lin *et al.*, 2012)

Figure 3.15 reveals a positive correlation between PET values and attendance during the cool season in areas A and B; i.e. in the winter, attendance increases as the thermal condition becomes warmer. As PET rises during the hot season, attendance increases correspondingly directly converse to the aforementioned relationship in the open square, as in Fig. 3.13, and is, therefore, worthy of further investigation.

To examine this phenomenon, the relationship between attendance distribution in the shaded and unshaded areas is considered. They investigated the proportion of people located in shaded areas according to the different PET groups in the entire Park. Figure 3.16 indicates the proportion of people staying in the shaded areas in regard to different PET groups. During both the cool and hot seasons, when PET was less than 30°C, few people chose to stay in the shaded spaces; i.e. the majority participated in activities in the unshaded spaces. However, when PET > 30°C, more visitors seek the shelter of the shade. When PET > 34°C, 70% of all attendees were situated in the shade; when PET was greater than 42°C, this ratio reached 90%. This indicates that as thermal discomfort increased,

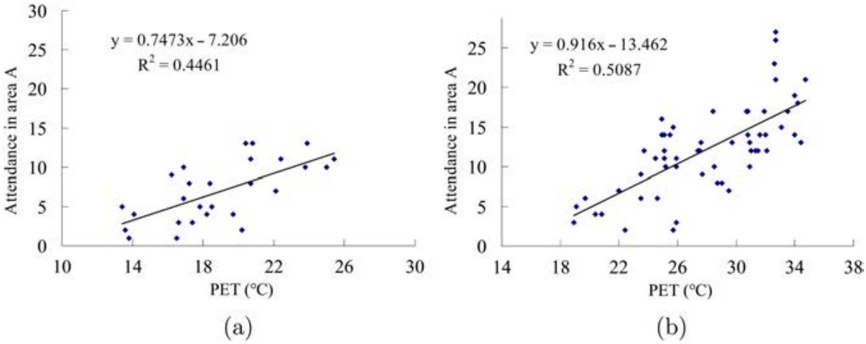


Figure 3.15. Relationship between PET temperatures and attendance at area A (shaded street region) during the (a) cool season; (b) hot season. (Source: Lin *et al.*, 2013)

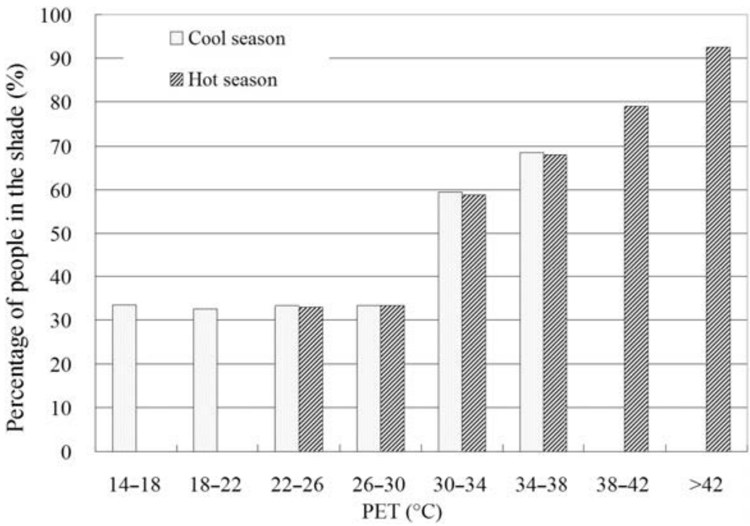


Figure 3.16. Ratio of PET temperature ranges and the percentage of people in the shade at each area. (Source: Lin *et al.*, 2013)

people gradually moved to spaces with high levels of shading, thereby relieving their discomfort.

Thus, the summer phenomenon of increasing attendance in this type of area with rising PETs can be interpreted as groups of people moving from one area to another according to their thermal preferences. That is, areas A and B have superior thermal comfort conditions relative to other areas without shading; therefore, people move from areas without shading to shaded areas for better thermal comfort. When PET is greater than 34°C in areas with higher shading during the hot season, PET in other unshaded areas reaches 40°C or higher, which is extremely uncomfortable. Therefore, people may move from unshaded areas to shaded areas. The results demonstrate that highly shaded spaces have positive benefits regarding park attendance when thermal conditions rise during both cool and hot seasons, which is especially important for sub-tropical regions due to the long periods of hot months.

They further discussed the first priority methods for local people to adjust to uncomfortable conditions outdoors, via the questionnaires. Figure 3.17 indicates that during the cool season, 45% of respondents selected ‘moving to shaded areas’, followed by ‘adjustment of clothing’ (25%) and ‘drinking beverages’ (18%). In the hot season, shading was the preferred choice to an even greater degree (62%) than during the cool season. Adjustments of clothing also fell by a significant amount, being selected by only 8% of respondents, even smaller than that for selecting drinking beverages. These results demonstrate that shading is the superior preference for people when adapting to a hot climate. This is extremely significant for tropical regions, whose climate patterns are characterized by a long hot season.

3.5 Design Mindset Regarding Shading Planning in the (Sub-)tropical Region

3.5.1 *Shading — key issue on outdoor space design in the (sub-)tropical region*

Tropical people have higher acceptance (tolerance) for high temperature due to the thermal comfort characteristic, but they still desire a lower thermal environment. If the solar radiation can be shaded effectively to reduce the mean radiant temperature, their satisfaction

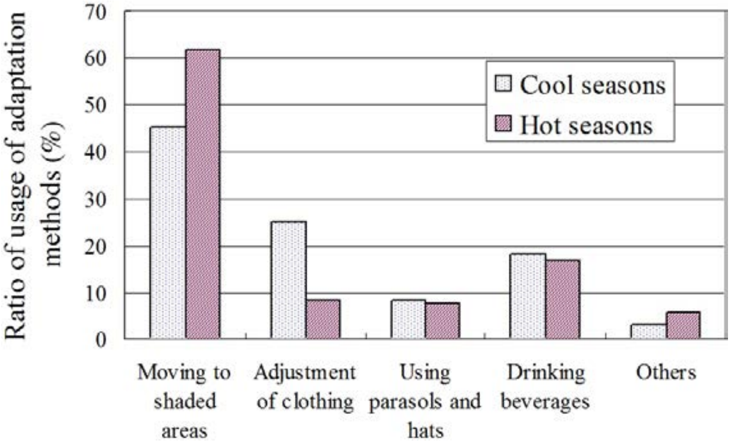


Figure 3.17. Ratio of usage of thermal adaptation methods during cool and hot seasons. (Source: Lin *et al.*, 2013)

would be enhanced. According to the actual measurement and simulation results of multiple shaded thermal environments, the shading level and material have significant effects on the mean radiant temperature, and good shading contributes to enhancing the long-term thermal comfort.

The research on countries in the temperate zone, such as the UK and Sweden, shows that as the temperature increases, more people would go to parks and squares, suggesting that a sunny sky attracts more people to enjoy the sun. However, the tropical studies find that the well shaded regions attract more people in summer or winter, indicating that good shading contributes to the optimal use of space, and people move into the shaded regions to mitigate their discomfort.

In tropical regions, the shading condition should be fully considered in the design of outdoor environments. At present, the designs of some (sub-)tropical parks and squares are based on the concepts adopted in countries in the temperate or frigid zones, namely setting extensively open and unshaded squares or lawns. As a result, the thermal condition becomes too high in the summer and the open areas are seldom used. Figure 3.18 describes the use status of two seating areas in a park recorded during the same period. As shown

Figure 3.18. Usage of the open space (a) and shaded space (b) in the same park. (Source: Photo by Hsiao-Chi Lien)

in Fig. 3.18(b), many people are sitting in the area of shading formed by dense arbor trees around. On the contrary, few people sit in the area shown in Fig. 3.18(a) because the rear planting cannot provide good shading around the seats. Figure 3.19 shows the distribution of users of an outdoor step square in the shading of different seasons, suggesting that whether in cool or hot seasons, people tend to choose places with shading for rest (Huang *et al.*, 2015). Hence, it is important to consider the tropical climate characteristics and people's preferences in the space design.

3.5.2 *Shading simulation tools*

Several auxiliary tools are available and can be used for diagnosis of the shading characteristics of outdoor environments. The most direct approach to diagnose on-site shading characteristics is to use the fisheye photo taken for a specific location. The photo can reflect the sheltering conditions from above. If it is overlapped with the

(a) (b)

Figure 3.19. Distribution of users of the outdoor step square under shadow conditions in summer (a) and winter (b). (Source: Photo by Hsiao-Chi Lien)

local sunshine path, it is possible to detect whether the sunshine, at that place, and in any month and period, would be sheltered by the plants or structures. At present, some models can be used for analysis of shading, counting hours of sunshine, or further T_{mrt} simulation, through the fisheye photo, such as the RayMan model (Matzarakis *et al.*, 2007; 2010). The overlapped fisheye photo and sunshine path image in Figs. 3.6 and 3.11 are made with the RayMan model.

If the fisheye photo of a certain location is not available, or future shading conditions need to be simulated in the early planning stage,

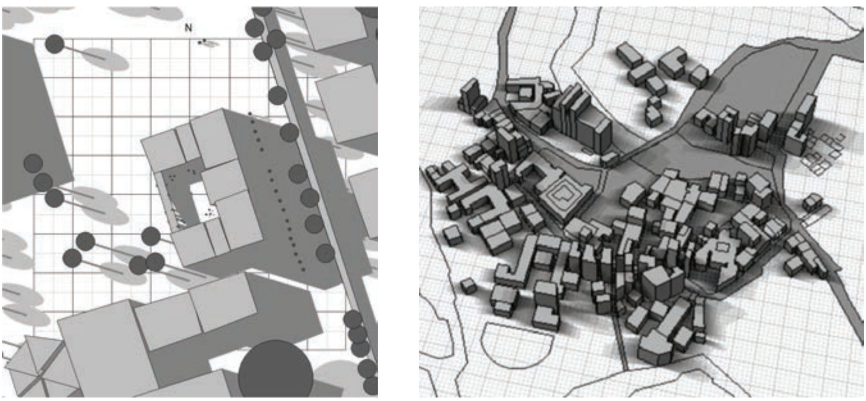


Figure 3.20. Shadow conditions at specific times simulates by RayMan model (left) and Ecotect (right) software. (Source: Photo by Se-Feng Chang and Yong-Chih Kuo)

other models or programs can be used to simulate the detail shading conditions by importing the virtual model of buildings, plants, and structures, such as the SkyHelios model (Matzarakis and Matuschek, 2011), ENVI-met model (Bruse and Fleer, 1998) or some developed programs embedded on the GIS platform. Those models can output an SVF distribution map for the designer to determine the place with a higher SVF (more open to the sky), in order to modify the original design plan or propose improvement countermeasures.

In addition to using SVF value to directly understand the shading characteristics of a space, a shadow map can be used to directly state whether such an area is sheltered during different dates and periods. Besides the models for academic application (such as the RayMan model), some common computer-aided design software (such as Ecotect, Vasari) can also create similar effects. Figure 3.20 shows the shadow map outputs of RayMan and Ecotect. Through such mapping, architects and planners may design a space with activities responding to shading characteristics. For example, an architect can design for the occasion of receiving full sunshine on a winter afternoon, as well as providing good shelter on a summer afternoon, in order to create a comfortable outdoor environment all year round.

(a) (b)

Figure 3.21. Example of creating good shelter with (a) natural plant and artifical structures. (Source: Photo by Tzu-Ping Lin)

3.5.3 *Implementation of shading design*

The effect of shading should be always considered in outdoor or semi-outdoor spaces such as passways, entrance hallways, arcades, bus stops, playgrounds for children and activity spaces for the elderly. As people are temporarily confined to those areas, their comfort should be a concern. In actual landscape design, if the space permits, arbors with large crown areas are the best choice, and partial artificial shading facilities can also create a good shading effect. Figure 3.21(a) shows an example of the famous Banyan Garden at National Cheng Kung University, which has a large banyan canopy of nearly 30 m and crown area up to 700 m^2, providing good shelter for the leisure and recreation of the public. During the hot summer noon, instead of staying on the grassland, most people gather under the tree shelter for diversified activities. Figure 3.21(b) illustrates the entrance design of the Tainan Municipal Sin-Nan Elementary School, where the hallway at the entrance is a space for students to wait for their parents or engage in social activities. The architect Mu-Hsien Liu set a large area of sun-shading facilities in front of the hallway, which provides good shading effects.

In detailed shading design, the shading ratio should first be increased, and the relative relationship between the year-long sun path and the users should be taken into account, in order to control where and when the shade occurs. In terms of selection of material, light-blocking and well-insulating material should be used to reduce excessive short-wave and long-wave radiation, so as to lower the mean radiant temperature of activity-related regions. For tropical areas, a cool environment can attract people, thus activating urban space and creating outdoor environments with higher thermal comfort and satisfaction.

References

ASHRAE (2001). *ASHRAE Handbook of Fundamentals*, American Society of Heating, Refrigerating and Air-conditioning Engineers, Inc., Atlanta, GA.

Ballantyne, E.R., Hill, R.K. and Spencer, J.W. (1977). Probit analysis of thermal sensation assessments, *International Journal of Biometeorology*, **21**(1), 29–43.

Brager, G.S., Paliaga, G., de Dear, R. *et al.* (2004). Operable windows, personal control, and occupant comfort, *ASHRAE Trans.*, **110**(2), 17–35.

Bruse, M., Fleer, H. (1998). Simulating surface-plant-air interactions inside urban environments with a three dimensional numerical model. *Environmental Modelling & Software* **13**(3–4), 373–384

de Dear, R.J. and Fountain, M.E. (1994). Field experiments on occupant comfort and office thermal environments in a hot-humid climate, *ASHRAE Transactions*, **100**(2), 457–474.

Dimoudi, A. and Nikolopoulou, M. (2003). Vegetation in the urban environment: microclimatic analysis and benefits, *Energy and Buildings*, **35**(1), 69–76.

Eliasson, I., Knez, I., Westerberg, U. *et al.* (2007). Climate and behaviour in a Nordic city, *Landscape Urban Planning*, **82**(1–2), 72–84.

Emmanuel, R. and 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.

Emmanuel, R., Rosenlund, H. and 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.

Fanger, P.O. (1972). *Thermal Comfort*, McGraw Hill, New York, NY.

Fanger, P.O. (1973). “Conditions for thermal comfort — a review”. In: *Proceedings of the Symposium on Thermal Comfort and Moderate Heat Stress* (CIB W45), Garston, 1973 Building Research Establishment, 3–15.

Feriadi, H. and Wong, N.H. (2004). Thermal comfort for naturally ventilated houses in Indonesia, *Energy and Buildings*, **36**(7), 614–626.

Giridharan, R., Lau, S.S.Y. and Ganesan, S. (2005). Nocturnal heat island effect in urban residential developments of Hong Kong, *Energy and Buildings*, **37**(9), 964–971.

Giridharan, R., Lau, S.S.Y., Ganesan, S. *et al.* (2007). Urban design factors influencing heat island intensity in high-rise high-density environments of Hong Kong, *Building and Environment*, **42**(10), 3669–3684.

Hamdi, R. and Schayes, G. (2007). Sensitivity study of the urban heat island intensity to urban characteristics, *International Journal of Climatology*, **28**(7), 973–982.

Höppe, P. (1999). The physiological equivalent temperature — a universal index for the biometeorological assessment of the thermal environment, *International Journal of Biometeorology*, **43**(2), 71–75.

Huang, K.T., Lin, T.P. and Lien, H.C. (2015). Investigating Thermal Comfort and User Behaviors in Outdoor Spaces: A Seasonal and Spatial Perspective, *Advances in Meteorology* (in press).

Hwang, R.L. and Lin, T.P. (2007). Thermal comfort requirements for occupants of semi-outdoor and outdoor environments in hot-humid regions, *Architectural Science Review*, **50**(4), 60–67.

Hwang, R.L., Lin, T.P. and Matzarakis, A. (2011). Seasonal effects of urban street shading on long-term outdoor thermal comfort, *Building and Environment*, **46**(4), 863–870.

Johansson, E. (2006). Influence of urban geometry on outdoor thermal comfort in a hot dry climate: A study in Fez, Morocco, *Building and Environment*, **41**(10), 1326–1338.

Johansson, E. and Emmanuel, R. (2006). The influence of urban design on outdoor thermal comfort in the hot, humid city of Colombo, Sri Lanka, *International Journal of Biometeorology*, **51**(2), 119–133.

Kántor, N. and Unger, J. (2011). The most problematic variable in the course of human-biometeorological comfort assessment — the mean radiant temperature, *Central European Journal of Geosciences*, **3**(1), 90–100.

Kántor, N., Lin, T.P. and Matzarakis, A. (2013). Daytime relapse of the mean radiant temperature based on the six-directional method under unobstructed solar radiation, *International Journal of Biometeorology*, **58**(7), 1615–1625.

Karyono, T.H. (2000). Report on thermal comfort and building energy studies in Jakarta, Indonesia, *Building and Environment*, **35**(1), 77–90.

Ketterer, C., Matzarakis, A. (2014). Human-biometeorological assessment of heat stress reduction by replanning measures in Stuttgart, *Germany, Landscape and Urban Planning*, **122**, 78–88.

Lin, T.P., Matzarakis, A. and Huang, J.J. (2006). "Thermal comfort and passive design of bus shelters", in *Proceedings of the* 23rd *Conference on Passive and Low Energy Architecture (PLEA2006)*, 6–8 September 2006, Geneva, Switzerland.

Lin, T.P. and Hsu, C.H. (2007). Thermal comfort survey and analysis of baseball stadium. Unpublished Bachelor Thesis, National Formosa University, Yunlin, Taiwan.

Lin, T.P. and Matzarakis, A. (2008). Tourism climate and thermal comfort in Sun Moon Lake, Taiwan, *International Journal of Biometeorology*, **52**(4), 281–290.

Lin, T.P. (2009). Thermal perception, adaptation and attendance in a public square in hot and humid regions, *Building and Environment*, **44**(10), 2017–2026.

Lin, T.P., Matzarakis, A. and Hwang, R.L. (2010). Shading effect on long-term outdoor thermal comfort, *Building and Environment*, **45**(1), 213–221.

Lin, T.P., de Dear, R. and Hwang, R.L. (2011). Effect of thermal adaptation on seasonal outdoor thermal comfort, *International Journal of Climatology*, **31**(2), 302–312.

Lin, T.P., Tsai, K.T., Hwang, R.L. *et al.* (2012). Quantification of the effect of thermal indices and sky view factor on park attendance, *Landscape Urban Planning*, **107**(2), 137–146.

Lin, T.P., Tsai, K.T., Liao, C.C. *et al.* (2013). Effects of thermal comfort and adaptation on park attendance regarding different shading levels and activity types, *Building and Environment*, **59**(1), 599–611.

Lin, T.P., Yang, S.R., Matzarakis, A. (2015). Customized rating assessment of climate suitability (CRACS): climate satisfaction evaluation based on subjective perception, *International Journal of Biometeorology*, **59**(12), 1825–1837.

Malama, A., Sharples, S., Pitts, A.C. *et al.* (1998). Investigation of the thermal comfort adaptive model in a tropical upland climate, *ASHRAE Transactions*, **104**(1B), 1194–1206.

Matzarakis, A. and Mayer, H. (1996). Another kind of environmental stress: thermal stress, *WHO News*, **18**, 7–10.

Matzarakis, A., Mayer, H., Iziomon, M.G. (1999). Applications of a universal thermal index: physiological equivalent temperature, *International Journal of Biometeorology*, **43**(2), 76–84.

Matzarakis, A., Rutz, F. and Mayer, H. (2007). Modelling radiation fluxes in simple and complex environments — Application of the RayMan model, *International Journal of Biometeorology*, **51**, 323–334.

Matzarakis, A., Rutz, F. and Mayer, H. (2010). Modelling radiation fluxes in simple and complex environments: basics of the RayMan model, *International Journal of Biometeorology*, **54**(2), 131–139.

Matzarakis, A. and Matuschek, O. (2011). Sky view factor as a parameter in applied climatology — rapid estimation by the SkyHelios model, *Meteorologische Zeitschrift*, **21**(1), 1–7.

McIntyre, D.A. (1980). *Indoor Climate*, Applied Science Publishers, London, UK.

Nikolopoulou, M., Baker, N. and Steemers, K. (2001). Thermal comfort in outdoor urban spaces: understanding the human parameter, *Solar Energy*, **70**(3), 227–235.

Oke, T.R. (1981). Canyon geometry and the nocturnal urban heat island: Comparison of scale model and field observations, *Journal of Climatology*, **1**, 237–254.

Oke, T.R. (1987). *Boundary Layer Climates*, Methuen, London, UK.

Paciuk, M. (1990). "The role of personal control of the environment in thermal comfort and satisfaction at the workplace", in Selby, R., Anthony, K., Choi, J. *et al.* (eds.) *Coming of Age*, Environment Design Research Association, Oklahoma, OK.

Shashua-Bar, L., Potchter, O., Bitan, A. *et al.* (2010). Microclimate modelling of street tree species effects within the varied urban morphology in the Mediterranean city of Tel Aviv, Israel, *International Journal of Climatology*, **30**(1), 44–57.

Thorsson, S., Lindqvist, M. and Lindqvist, S. (2004). Thermal bioclimatic conditions and patterns of behaviour in an urban park in Goteborg, Sweden, *International Journal of Biometeorology*, **48**(3), 149–156.

VDI (1998). Methods for the human biometeorological evaluation of climate and air quality for the urban and regional planning. Part I: Climate, *VDI guideline 3787, Part 2*, Beuth, Berlin, Germany.

This page intentionally left blank

Chapter 4

Urban air ventilation in high-density cities in the tropics

Edward Ng

4.1 Introduction

More high-density cities are going to appear in tropical regions as their countries are urbanizing. In some parts of the world, especially in the Far East and in China, settlements that were villages only 30 years ago are now sprawling metropolises. For example, in 1979 the township of Shenzhen in China had a population of only 300,000. This number has increased to over 10 million in 2011. It has grown from a collection of small villages to an urban conglomerate of 2,000 km^2 with a metro city core of 400 km^2.

The urbanization process inevitably means that more buildings need to be constructed and higher density urban living needs to be endured. Taking Shenzhen again as an example, its urban density is on the order of eight to nine thousand per square kilometer. This number is easily double that of many large cities including London, Paris and New York.

From an urban air ventilation point of view, a higher number of, taller, bulkier and closely packed buildings in the urban areas means that the roughness of the land surface will increase. The displacement height, and thus the urban canopy height, of the city will thicken.

The available incoming wind to the city will be slowed. On the other hand, more intense urban activities mean that more anthropogenic heat and air pollution are generated. This requires good urban air ventilation to carry them out of the city. This is the problem that city planners face.

How much urban air ventilation does the city need, and for what kind of benefit? Is wind available? What is the optimal city density? How should one plan the city in order to optimize the benefits of the available wind? How tall should the buildings of the city be? How to plan the roads, the spaces and the buildings? And so on. These are some of the question being asked.

4.2 What Urban Air Ventilation Does a City Need?

One may start estimating the need for urban air ventilation by referring to ASHRAE 55 2013. This standard provides a useful understanding of the subject. Referring to the Graphic Comfort Zone Method of the standard (simplified and represented in Fig. 4.1), the maximum comfort operative temperature given the higher humidity of the tropics is about 27.5°C. This is the condition without any sensible air movement over the human body. The maximum comfort operative temperature may be increased if air movement is introduced. Referring to the acceptable ranges of operative temperature, as in Fig. 5.3.3.A of the standard (simplified and represented in Fig. 4.2), at an air speed of 1 m/s, the maximum comfort operative temperature may be extended to 30.5°C. That is to say, a 1 m/s air speed may compensate for an increase of about 3°C in operative temperature. The standard thus provides an understanding of how an increase in air movement may extend the comfort range of adaptive thermal comfort. Bearing in mind that outdoor thermal comfort sensation is closely related to the human body's adaptive sensation, the adaptive understanding may be more relevant. Referring to the "increases in acceptable operative temperature limits in occupant-controlled naturally conditioned spaces resulting from increasing air speed above 0.3 m/s" (Fig. 5.3.1 of the standard), it can be noted that, in a

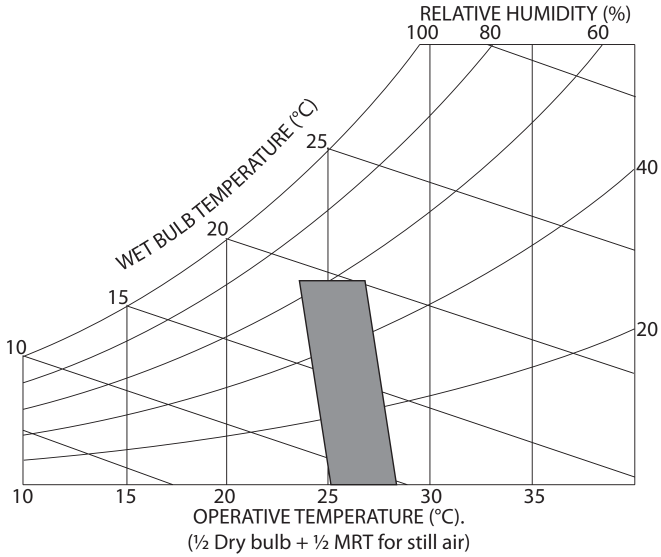


Figure 4.1. Maximum comfort operative temperature in Graphic Comfort Zone method. (Source: Author)

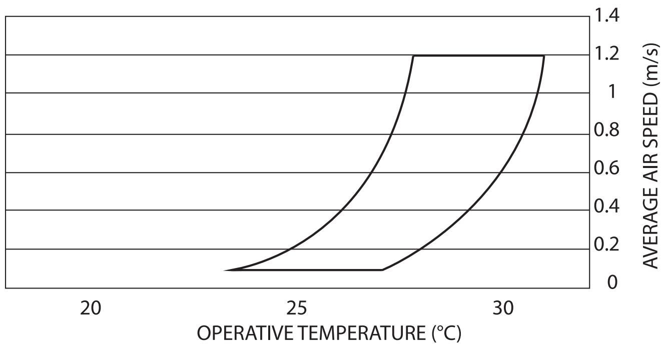


Figure 4.2. Acceptable ranges of operative temperature. (Source: Author)

warmer environment, an increase of the operation temperature by 2.2°C is allowed. All in all, ASHRAE 55 2013 points to the thermal comfort range being increased by 2–3°C when air ventilation is provided.

The physiologically equivalent temperature (PET) is a bio-meteorological comfort model developed by Höppe (1999):

> *Regulatory physiological processes can affect the relative importance of meteorological parameters, e.g. wind velocity becomes more important when the body is sweating. In order to take into account all these factors, it is necessary to use a heat-balance model of the human body. The physiological equivalent temperature (PET) is based on the Munich Energy-balance Model for Individuals (MEMI), which models the thermal conditions of the human body in a physiologically relevant way. PET is defined as the air temperature at which, in a typical indoor setting (without wind and solar radiation), the heat budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed. This way PET enables a layperson to compare the integral effects of complex thermal conditions outside with his or her own experience indoors.*

Based on the PET formulation, the following simplified equation (Eq. 4.1) may be written for the typical climatic conditions of the tropics.

$$\mathrm{PET} = 1.2T_a - 2.2v + 0.55(T_{mrt} - T_a), \tag{4.1}$$

where PET physiological equivalent temperature in °C
Ta air temperature in °C
$Tmrt$ mean radiant temperature in °C
v air speed in m/s.

In short, a 1 m/s increase in air speed may compensate for a 1.8°C increase in air temperature. This is slightly less than the number obtained using the ASHRAE 55 2013 standard, but the two results are very similar.

Based on a longitudinal outdoor thermal comfort study in Hong Kong, Cheng *et al.* (2010) concluded "the effect of increasing wind speed from 0.3 m/s to 1 m/s is equivalent to a drop of about 1.9°C in air temperature." This finding is comparable to a study by Khedari in Thailand that a 2°C rise in comfort temperature was observed for an increase of wind speed in the same range (Khedari *et al.*, 2000).

Thus, an easy-to-understand planning rule of thumb could be: *providing an urban air ventilation of 1 m/s can mitigate a 2°C rise in air temperature.*

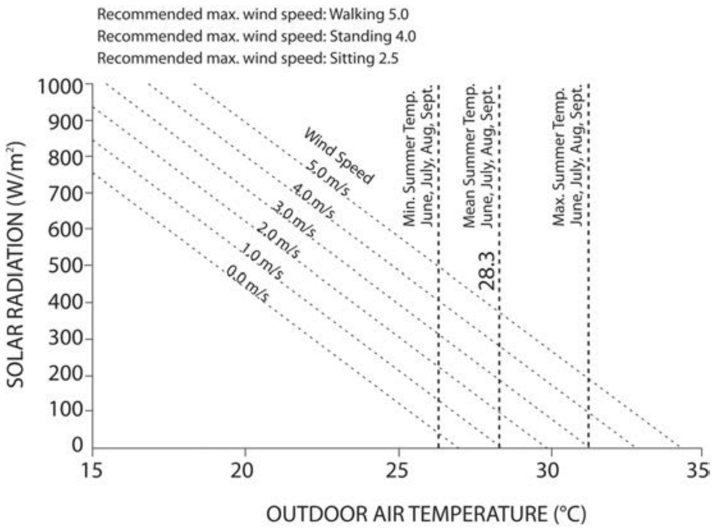


Figure 4.3. A simplified comfort outdoor temperature chart. (Source: Author)

Now that one can reasonably estimate the benefit of urban air ventilation to improve human comfort, the next question to ask is how much is needed. Keeping in mind the high ambient humidity level (relative humidity (RH) in the summer months could be on the order of 70–80% in the tropics), Cheng and Ng (2006) provided a simple graphical method (simplified and represented in Fig. 4.3). The y-axis of Fig. 4.3 is solar radiation. A person under the sun receives approximately 700–900 W/m^2 (watts per square meter) of solar radiation, whereas a person standing under shade surrounded by buildings receives, indirectly, approximately 100–150 W/m^2 of solar radiation. The x-axis is the outdoor air temperature. The diagonal axis is the air speed, from calm air of 0 m/s to high wind speed of 5 m/s. The minimum, mean and maximum summer temperatures are plotted. In the case of Hong Kong, the mean summer air temperature from June to September is about 28.3°C; hence, with 100 W/m^2 of solar radiation, the required urban air speed is on the order of 1.5–2.0 m/s.

By the way, the graph provides another message to the planners in Hong Kong: provide shade first, and then provide wind. Furthermore, lower the daytime air temperature by providing greenery and cool spots.

A similar way to work out the needed urban air ventilation of one's own city could follow Cheng's logic.

1. Establish the urban comfort temperature, in terms of PET or some other thermal comfort model, or by conducting user surveys.
2. Obtain the climatological data of the city by referring to the local observatory's measurement data.
3. Factor in the urban area's urban heat island (UHI) intensity if necessary.
4. Estimate the needed air speed based on reasonable assumptions of the other environmental parameters.
5. Check that the resultant range of air speed is within reasonable limits for human activities.
6. If not, mitigation measures beyond the provision of urban air ventilation may be needed.

Having considered Cheng's study, it is important to point out that the matter of urban thermal comfort is more complicated than that due to the dynamic nature of the outdoor thermal environment. Chun and Tamura (2005) recommended that the understanding must be spatially related. Therefore it is not the thermal consideration at one point that is important, but the consideration taking into account the pedestrian's route before arriving at the point. At this juncture, I reckon further research is needed. In particular, it is recommended that de Dear's notion of Alliesthesia (de Dear, 2009) be looked at, and for bedtime reading Heschong's *Thermal Delight in Architecture* (1979).

4.3 Is Wind Available?

Once the need for wind and its likely magnitude are established, the next question to ask is whether or not the city has the needed wind, how much, and from where? This is where planners need to enlist the help of meteorologists and climate scientists. It is also where the measured records of the city's weather stations become useful.

The weather service of the city typically has a number of stations in and/or around the city. They are good starting points.

Before going into the details, it is useful that one has a bit of background understanding of the characteristics of wind in the tropics in general and in one's city location in particular. In the tropics, the trade wind is the prevailing pattern of easterly surface wind towards the equator; the wind blows from the northeast and from the southeast respectively in the northern and the southern hemisphere. A monsoon is seasonal and dominates from May through July (i.e. the hotter summer months) in the Asian, African and American continents. Monsoons are essentially large-scale sea breezes that occur when the temperatures on land are significantly warmer or cooler than the temperature of the ocean. Taking the areas around Hong Kong as an example, the summer East Asian monsoons are driven by the temperature differences between the Asian continent and the Pacific Ocean. The prevailing wind directions are southerlies when the summer monsoon reaches Hong Kong during the summer months. This contrasts sharply with the prevailing trade wind from the east and the winter monsoons from the north and the northeast.

By the way, it is useful to note that the summer monsoons bring in moist air from the sea. This increases precipitation and the humidity content of the air. For example, the mean summer relative humidity is high at 74%. High humidity has an impact on thermal comfort.

A city's reference wind station is normally located on a spot that is least affected by the city itself and the city's immediate surroundings. Hence, it is typically sited in the airport or on an open field. In Hong Kong, the recognized reference wind station is located on a small island (Waglan Island) some 20 km southeast of Hong Kong's land mass (mast height 68 m above mean sea level). When its three wind roses (Fig. 4.4) are compared, the characteristics of Hong Kong's trade and monsoon winds can be noted. In this particular case, it is noted that annually speaking, the prevailing wind is from the east, although the summer wind rose indicates that the important summer wind is actually coming from the southwest. It is also on the whole weaker than the easterly or the northerly wind.

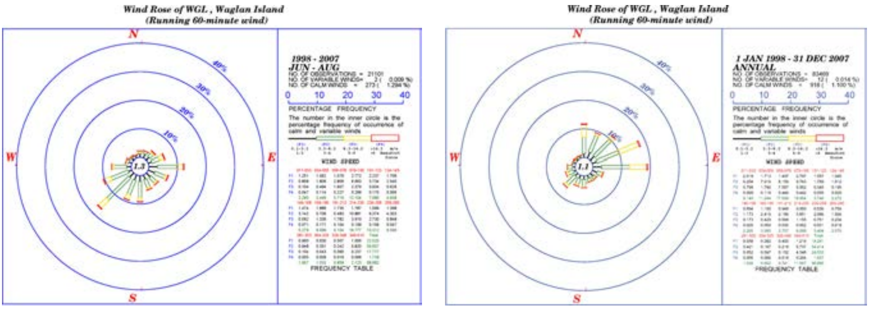


Figure 4.4. Annual and summer wind roses of the reference wind station, Waglan Island, from 1998 to 2007. (Source: Hong Kong Observatory)

The reference wind data mentioned above provides the wind available to the city in general. The next step is to understand how the wind interfaces with the city, and what wind will finally arrive on the building site or in an urban area within the city. This step cannot be underestimated. For cities next to the sea and/or surrounded by hills and water bodies, the site wind characteristics can be significantly different from that measured in an airport 10 or 20 kilometers away. Both the wind speed and direction may be different. This can be illustrated with the collated wind roses of the summer months of Hong Kong as shown in Fig. 4.5. It can be noted that the wind roses of the urban areas differ drastically from the wind rose of the reference station (far right corner of the figure). This is due partly to the topography of the territory (mainly affecting wind directions) and partly to the urban structure of the city (mainly affecting wind speeds).

To account for the effects of the site's surrounding topography, wind tunnel tests using 1:1000 or 1:2000 models are typically employed. An example is illustrated in Fig. 4.6. There are two guidelines governing its proper process (ASCE, 1999; AWES, 2001). The test allows for the weakening of the wind speed due to surface roughness to be quantified, as well as the blocking, channeling and re-directing effects due to hills. The test works well for the more synoptic-based mechanical — or momentum-driven — wind to be studied. The 16-direction wind profiles the turbulence intensity, and the wind probability tables of the site may be obtained.

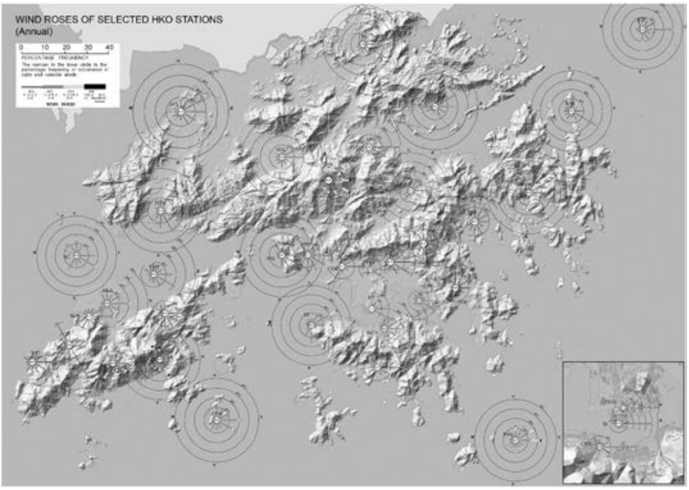


Figure 4.5. The wind roses of the month of July of observation stations of Hong Kong Observatory. The reference station (Wanglan Island) is at the right corner of the figure. (Source: Author)

Figure 4.6. Topographical model of Table Mountain in the wind tunnel. (Source: Dr Adam Goliger)

The wind engineering circle has been using large-scale models in the wind tunnel as described above for wind load, wind safety, and other wind-related studies. The methodology is well proven. However, for urban air ventilation studies that focus primarily on synoptic conditions where weak wind dominates, the topographical model approach on its own may not be sufficient. In addition, for cities surrounded by the sea where land-sea breezes dominate, a study based on the synoptic-based mechanical wind may not be able to account for the diurnal patterns of the wind environment in different parts of the city. For example, under calm wind conditions, depending on how the land is orientated towards the sea, one area in the city may have easterly wind while another area has westerly wind.

This brings us to the need to utilize other techniques to complement the wind tunnel study. Modern mesoscale wind modeling may offer help here. It has the advantages of accounting for land-sea breezes, mountain valley breezes, and other kinds of thermally induced air movements. Recent scientific advances have improved its accuracy, and the availability of low-cost, high-performance computers has spread its accessibility. This method has gained popularity recently due to the need for mapping the wind availability data for renewable energy studies. The starting point of a successful mesoscale simulation is to create a surface model at a crude level of 1.5 km to 5 km cells. For each cell, data describing both terrain elevation and local surface roughness is used. Based on synoptic boundary condition data (from General Circulation Model results) and local measured station records, the whole model of perhaps 40 km^2 to 100 km^2 will be simulated throughout the depth of the troposphere. The wind speeds above the ground surface (60–500 m) are calculated using atmospheric boundary layer model. A popular model is NCAR's WRF model.[1] A finer-scaled model like the CALMET model[2] may be used to decrease the cell size to 100×100 m. This is useful for urban-level project studies.

[1] http://www.wrf-model.org/
[2] http://www.enviroware.com/calmet/

By collating all the available wind data (measured, experimented and simulated), it is possible to summarize them so that the site wind availability data of a project or an urban area may be characterized. This should be done by assembling the 16 directions of the data in terms of their

(1) wind profiles 10–600 m;
(2) wind turbulence intensity profiles 10–600 m,
(3) wind speed and probability data at 50 m, 100 m, 200 m and 500 m, and
(4) wind roses at 50 m, 100 m, 200 m and 500 m.

Apart from making reference to the annual wind, for urban thermal comfort it is also important to look at the summer wind; sometimes they are different. The wind roses at different heights should be able to inform how the surrounding topography affects the wind directions. Since it is the wind in the urban canopy layer (UCL) that is more of an interest to planners, the lowest wind rose should be more relevant. However, it is still important to compare, say, the 50 m wind rose to the 200 m wind rose to detect any anomalies. A learned guess is sometimes still needed so that a characteristic set of wind profiles, wind turbulence intercity profiles, and wind roses can be assembled for further studies.

The site wind availability data can inform the planner if wind is available, when it is available, and where it comes from. For example, if 1.5 m/s wind (at 2 m above ground) is beneficial for the summer months, by referring to the wind speed and probability data, it is possible to deduce the percentage of hours in the summer months that such wind is available to the site. If, for example, the site has 2 m/s wind available 50% of the time, then the planners know they should find ways to plan with the available wind. However, if the site only has 0.5 m/s wind available 50% of the time, then other mitigation measures may be needed.

The site wind availability data can be used as the inlet boundary condition for further microscale neighborhood-, street-, and building-level wind studies.

4.4 What is the Optimal City Density and How Tall should the Buildings be?

Suppose it is determined, based on the method as described in Sec. 4.3 above, that wind is available and that planners need to optimize it for the benefits; then, the question is how? An engineering approach is for the planners to design a scheme and then subject it to testing. Based on the tested results refinements may be made. The process can be iterative and time consuming. It does not tell the planners "how" to begin with either.

By contrast, the pre-emptive and informative approach provides the planners with some rule-of-thumb and ballpark numbers to begin a plan with. Recognizing that the few initial planning parameters are (A) site coverages and (B) building plot ratios, it is possible to parametrically work out how they affect the wind environment of the project so that planners know, roughly speaking, what plot ratios, site coverages, and building forms may be used to begin the plan given the location.

Before we go on further, it is useful to introduce a concept here. Wind velocity ratio (VR_w) is the ratio between the wind speed 2 m above ground (at the pedestrian level) and wind speed at the boundary layer level (i.e. at a theoretical height that wind is not affected by the ground roughness, which is typically set at 200 m above calm water surface and 500 m above cities). Wind speed at the boundary layer level is regarded as the reference wind of the site. Site wind availability studies, as explained in Sec. 4.3, allow one to obtain this reference wind. It is always useful to relate the wind speeds at different heights and at the ground level to this reference wind by means of the concept of VR_w (Fig. 4.7).

Coming back to the planning parameter of site coverage (GC), study results are available relating GC with VR_w (Kubota *et al.*, 2008; Yoshie *et al.*, 2008). Based on Tokyo's and Hong Kong's urban morphologies, Yoshie deduced that there is a linear relationship between site coverage and VR_w (Fig. 4.8). In a nutshell, the more ground is occupied by buildings, the less availability of wind one can have in the open area.

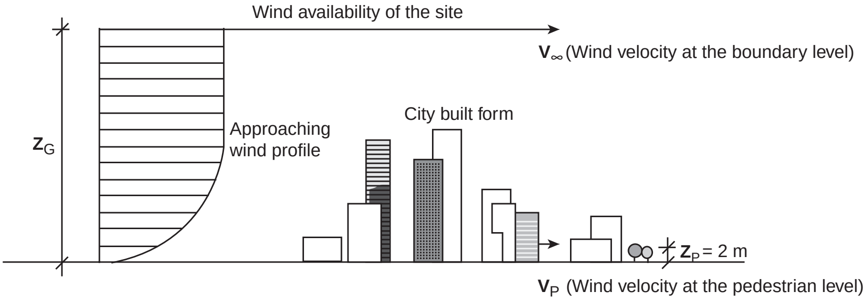


Figure 4.7. The concept of wind velocity ratio. (Source: Author)

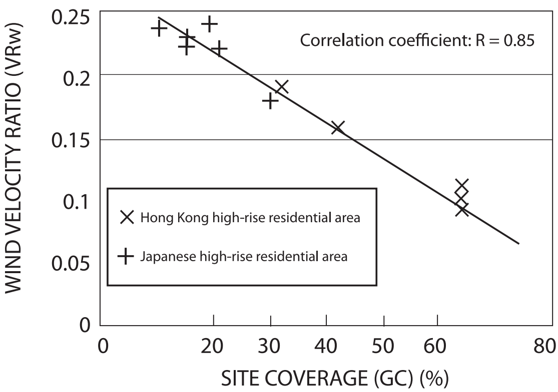


Figure 4.8. Linear relationship between site coverage and VR_w of Hong Kong and Japan. (Source: Author)

Regarding building's plot ratios, tall and bulky buildings increase the surface roughness of the land. A way to quantify the effect is to calculate the frontal area density (λ_f) of a collection of buildings in the neighborhood (Ng *et al.*, 2011). For example, for a high-density neighborhood of 300 × 300 m, between the spatial zone of 0 m to 60 m from the ground, the relationship between VR_w and λ_f can be obtained from the following equation:

$$\lambda_f = 2 - 5.6VR_w. \tag{4.2}$$

If the incoming wind at the boundary height level (500 m above ground) is 5 m/s, then at 2 m above ground the VR_w on a piece of flat ground should be about 0.45 (using log law with $\alpha = 0.15$). The site wind availability at 2 m above ground level in the open is on the order of 2.25 m/s. Any building to be constructed on it will reduce the available wind. Taking the design of a high-density neighborhood in Hong Kong in the Mong Kok metro areas as an example, if a 1 m/s wind on the ground level is desired, then based on the site wind availability data and Eq. 4.2, VR_w should be 0.2 and λ_f should be controled to less than 0.9. However, as it currently is, the average building heights in Mong Kok are on the order of 40–60 m, the buildings are bulky, and the streets are narrow (between 25 m and 40 m), so the range of λ_f is on the order of 0.6–1.5. The resultant VR_w is on the order of 0.25–0.1. Therefore, the wind availability is around 1.25–0.5 m/s. That is to say some areas in Mong Kok are already overbuilt from an urban air ventilation perspective.

Likewise, returning to the planning parameter of site coverage, if a VR_w of 0.2 is desired, then the overall ground coverage of the neighborhood should be kept under 30%. Say, for example, the roads and public open spaces occupy half of the land area; it means that in order to keep the overall site coverage to 30%, building projects may only occupy 60% of their project site area.

With the above ballpark figures in mind, planners can already design, at the master planning level (up to 1:5000), the size, scale, and capacity of the neighborhood. The basic land-use zoning and activity planning can also be done. At this planning level, the basic road patterns, the spatial infrastructure layouts, the building lot sizes and shapes, and their intensity can all be laid in accordance with the λ_f and GC understandings.

4.5 How to Plan the Details: the Roads, the Spaces and the Buildings

Once the λ_f and GC are understood on a broad basis, the next step is for the planners to have a better understanding of how the building should sit on the project site. There are no hard and fast quantitative rules here, but a few qualitative and diagrammatic guidelines may help (Ng, 2009). In the Hong Kong Planning Standards and

Guidelines (HKPSG)[3] at the website of the Planning Department of the Hong Kong SAR Government, one may refer to Chapter 11 on urban design. There is also a section on air ventilation. It has 12 tips on how projects may be designed to optimize the available wind at the district and the site level. In addition, the website of the City of Stuttgart has an online publication titled *Climate Booklet for Urban Development*.[4] This contains useful references for planners.

At the city level of planning for urban air ventilation, there are a number of important design features that planners must note. Firstly, based on the summer prevailing wind directions, the zoning of the sites must be packaged according to the following criteria.

(1) Smaller buildings in terms of footprint and lower buildings in terms of height should be planned to front the areas at the upstream wind, for example on the waterfront. Taller buildings may then be planned on the inland sites; this allows wind to penetrate further inland. However, in most cases, this has never been easy, as these sites are normally prime real estate. Therefore, due care must be exercised by the planners to allow for point blocks instead of flat slabs along the edge (Fig. 4.9).

(2) Long and continuous site packets perpendicular to the summer prevailing wind directions must be avoided. This is to prevent the forming of large wake areas behind the buildings. Ideally, long strips of land should be divided with intervening roads, footpaths and open spaces (Fig. 4.10).

(3) For waterfront sites, since wind normally comes from the smoother water surfaces, it is desirable to have a strip of public promenade along the waterfront so that city inhabitants may escape from the city core to enjoy the unobstructed wind over the water body (Fig. 4.11).

Secondly, at the city planning scale, adequate and sufficiently wide breezeways must be planned into the city's fabric. Breezeways must

[3] http://www.pland.gov.hk/pland_en/tech_doc/hkpsg/full/ch11/ch11_text.htm
[4] http://www.staedtebauliche-klimafibel.de/?p=0

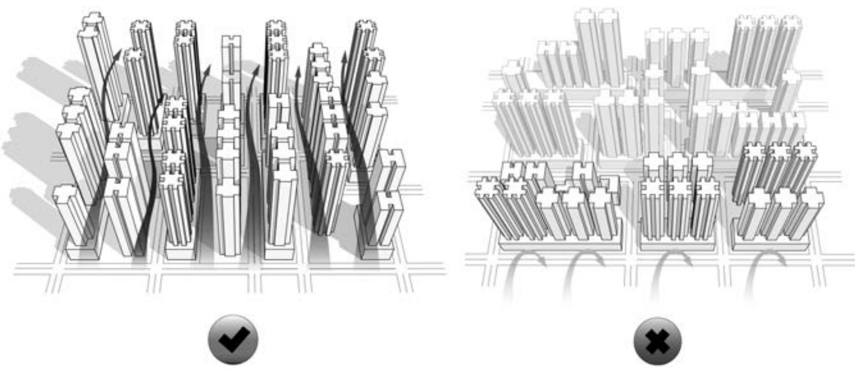


Figure 4.9. Point blocks instead of flat slabs to the areas at the upstream wind and on the waterfront to allow wind penetration into inner city. (Source: Author)

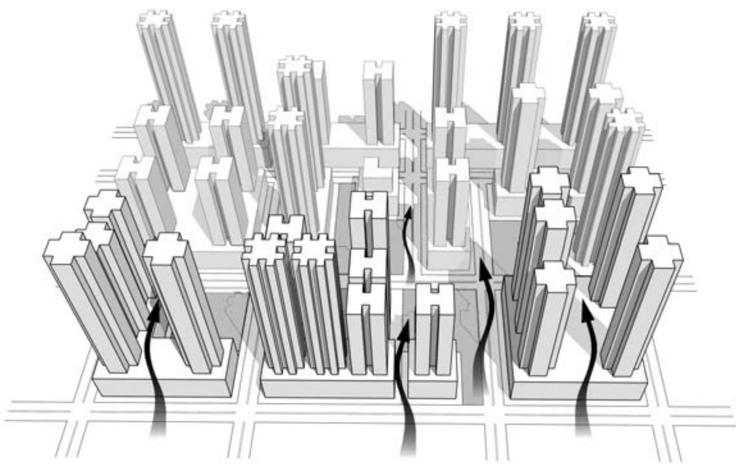


Figure 4.10. Long and continuous site packets should be avoided and divided with intervening roads, footpaths, and open spaces for better air ventilation. (Source: Author)

align with the prevailing wind directions. This allows wind to penetrate deeper into the inland areas. Linear city parks, a strip of land designated as low building zones, and wide tree-lined boulevards can be good breezeways. Breezeways are typically wide; it is not uncommon for a city to have a number of 50-m- to 100-m-wide breezeways planned into its fabric. They are particularly useful to connect across

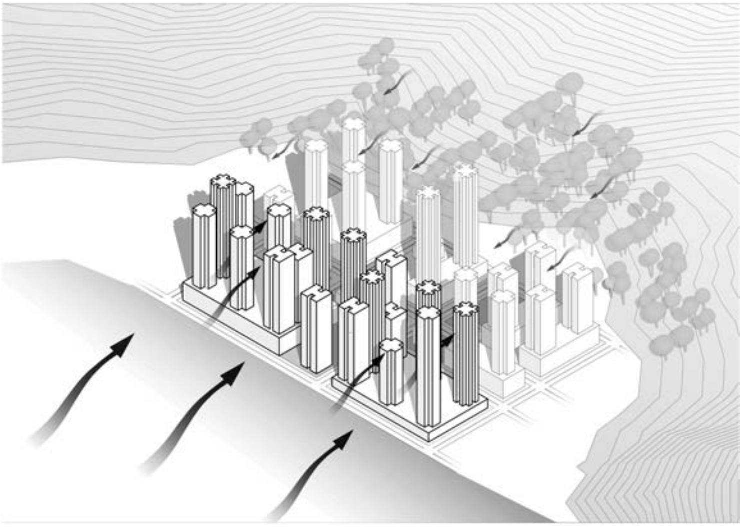


Figure 4.11. Unobstructed wind over the sea for waterfront sites. (Source: Author)

the city from the waterfront at its one end and the vegetated hill slopes at the other. This kind of breezeway captures the land–sea airflows very well. Breezeways must be planned together with the smaller but more numerous air paths so that wind can be channeled into the city's neighborhoods. Air paths increase the permeability of the city and allow wind to move around more freely. In general the intervals of air paths should be related to the width of the roads perpendicular to and intercepting them. Roughly speaking, air paths should be spaced at an interval five times the width of these roads. For effective urban air ventilation, breezeways and air paths should be perpendicular or at an angle to each other and extend over a sufficiently long distance for continuity — the key word here is continuity (Fig. 4.12).

Thirdly, it is useful to align the major streets, in parallel or up to 30°, along the summer prevailing wind direction. The length of the street grid perpendicular to the wind should be as short as possible. This is to minimize the stagnant zones while maximizing the effectiveness of wind across the urban area. Building project sites should

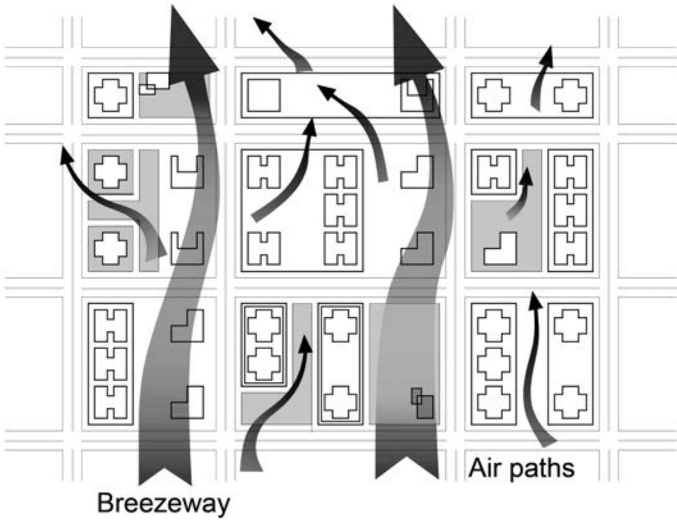


Figure 4.12. Breezeways and air paths should be connected and extended for continuity. (Source: Author)

be laid out and orientated to maximize urban air ventilation by aligning the longer frontage parallel to the wind direction (Fig. 4.13).

Fourthly, at the district scale of planning, say for a neighborhood of 500×500 m with about 100 or more building blocks, it is useful to design into it a height variation profile. If one takes a mean neighborhood building height of 40 m, then a profile of buildings from 15 m to 60 m may be designed (Fig. 4.14). The occasional tall building acts as a scoop or a rod so that wind from the upper level may be brought down or spiraled down to the ground. Coupled with an open space at the foot of the tall building, urban air ventilation can be greatly improved. Air paths can also be designed to extend from the open space into the urban fabric. A mixed building height skyline also helps to improve turbulence diffusion of air, which benefits pollution dispersion. One important aspect is to check for problems during strong gust wind conditions; tall buildings can amplify the wind speed and may cause local discomfort and create unsafe spots.

Fifthly, open spaces should be strategically designed into the city (Fig. 4.15). If the same area of open spaces is provided, then a collection of smaller and distributed parks is better than a single large

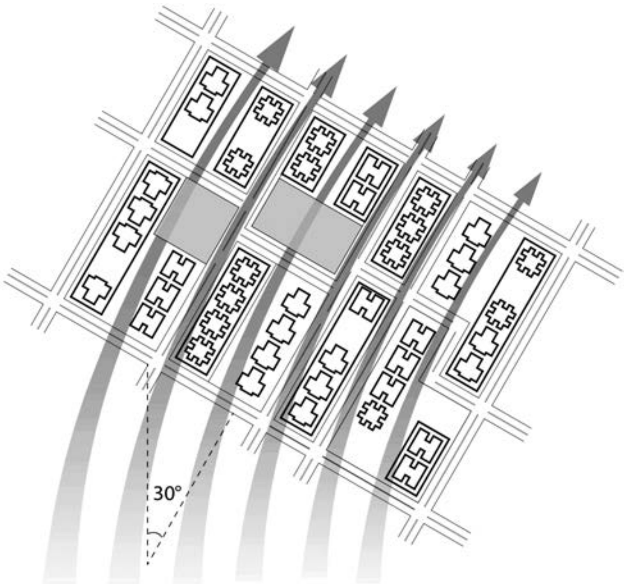


Figure 4.13. Aligning street orientations properly to promote better ventilation. (Source: Author)

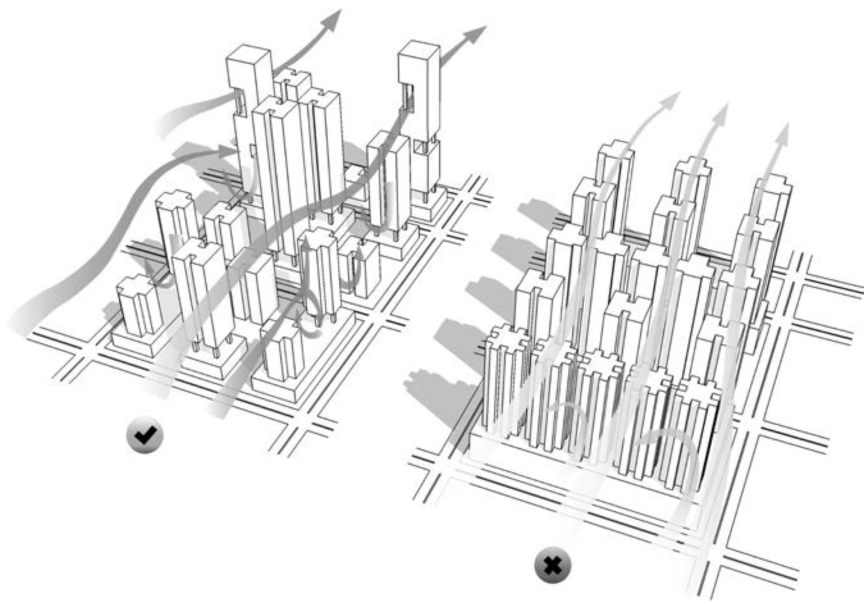


Figure 4.14. Varying building height in neighborhood planning for better air ventilation. (Source: Author)

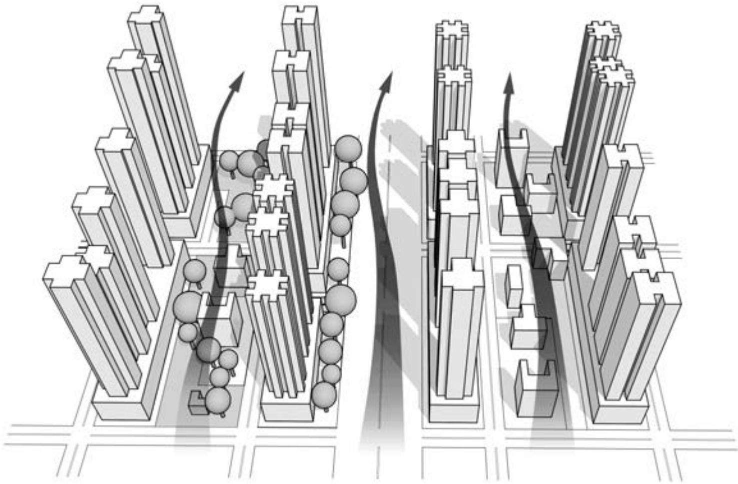


Figure 4.15. Linkage of open spaces to form breezeways or ventilation corridors. (Source: Author)

park. If the surrounding buildings were on average 40 m tall, then a park 100 × 100 m would be able to allow wind to flow over the roof tops and come down to the ground level. The most important point to bear in mind is to find ways to 'connect up' the open spaces from the windward to the leeward side. Continuity of openness is the key concept always to bear in mind when designing breezeways, air paths and open spaces. Tree planting may slow the wind, but if carefully located, it can allow the wind to pass through and at the same time provide shade and cool spots.

Once the planning of the city, district and neighborhood level is decided, it is useful to look further into the building project designs to optimize urban air ventilation. At this level, the disposition, permeability, height and form of the building design will affect the local urban air ventilation environment. Firstly, the deposition of buildings on one project site should respect its surrounding air path connections. For example, it should not abruptly terminate an air path that leads to the site. Instead, buildings can be stepped to provide gaps for the air path to continue (Fig. 4.16). Furthermore, wall-like blocks perpendicular to the prevailing summer wind directions must be avoided.

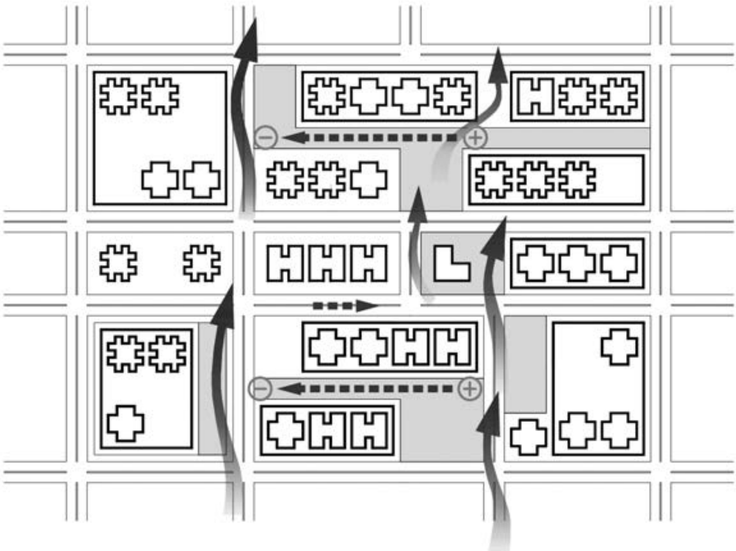


Figure 4.16. Building setbacks to provide gaps for air path connections. (Source: Author)

Secondly, perforations especially at or near the ground level must be maximized (Fig. 4.17). This increases the air volume near the ground and therefore improves urban air ventilation. In Hong Kong and in Singapore, two building forms prevail. In Hong Kong, building towers sit on a podium that occupies much of the open space at the ground level. This morphology can be described as the 'birthday cake form'. In Singapore, buildings sit on pillars that provide a shaded deck underneath. Of the two forms, the Singaporean one is far better in terms of providing better urban air ventilation. In addition, the 'shaded' void deck created provides a comfortable resting place for the inhabitants. In the case of Hong Kong's birthday cake form, if the podium can be designed to be stepped and a void incorporated between the podium and the tower, then urban air ventilation will be greatly improved.

Thirdly, for cities with tall tower blocks, inner-block building permeability should be designed into the building form (Fig. 4.18). The interplay of shapes that results in holes and gaps within the

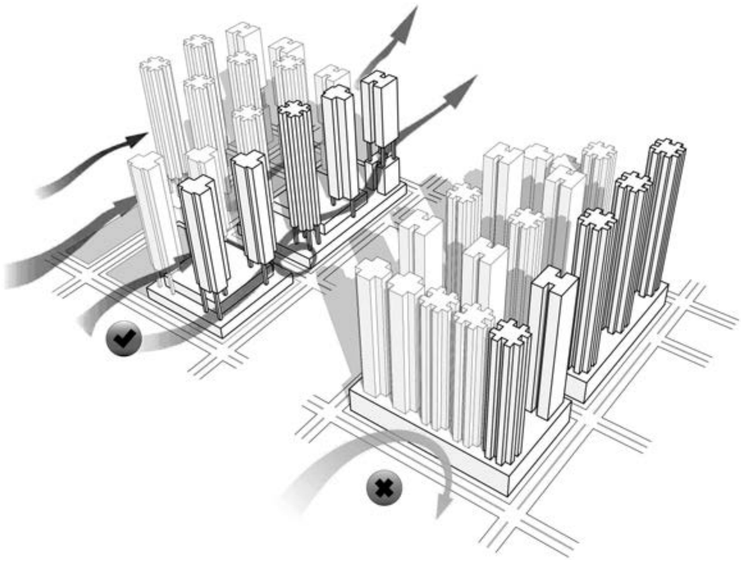


Figure 4.17. Stepping podia to improve air ventilation near the ground level. (Source: Author)

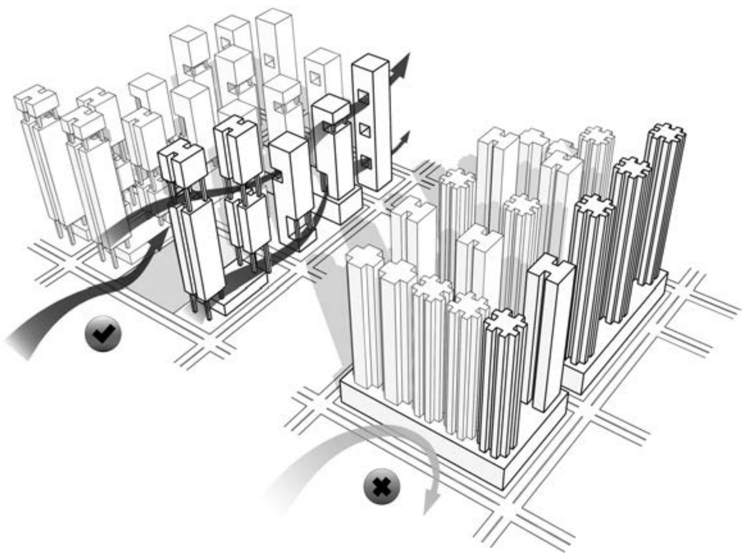


Figure 4.18. Creating gaps within the building for higher building permeability. (Source: Author)

building along with sky gardens are welcome design features. While the porosity created improves urban air ventilation, the shaded voids also give comfortable resting spaces.

4.6 A Case Study: Air Ventilation Assessment in Hong Kong

Further to the basic principles described in the previous sections of this chapter, it is now useful to give an example. In 2003, Hong Kong suffered the severe acute respiratory syndrome (SARS) outbreak. It was deemed that the congested urban living environment with its lack of light and air might be a contributing factor. The HKSAR Government then initiated a couple of studies. One of them was the study on establishing an air ventilation assessment (AVA) system. The idea was to develop an objective method to evaluate how a project might affect the urban air ventilation performance of its neighborhood. In 2006, the study was completed and the HKSAR Government then promulgated the Air Ventilation Assessment Technical Guidelines (AVA-TC06-01). A new chapter (Chapter 11-Urban Design: VA) was also incorporated into the HKPSG. The two documents were a first in addressing the weak wind problems of the city.

An immediate application of the AVA-TC06-01 (DevB, 2006) and Chap. 11 of HKPSG (HKPSG, 2014) was the re-planning of the old Kai Tak airport in the metro area of the city of Hong Kong (HKSAR, 2007) (Fig. 4.19). The site, just under 300 ha, is located on the east of the Kowloon peninsula. The eastern wind comes to this area over the sea before flowing inland. It is hence an important site from a city ventilation point of view. To ensure that future developments are properly planned and designed, the Planning Department of the HKSAR Government implemented a number of planning strategies.

(1) The major streets will align with the prevailing winds from the southeast.
(2) Building densities are limited, depending on the project site's location as related to the air path system.

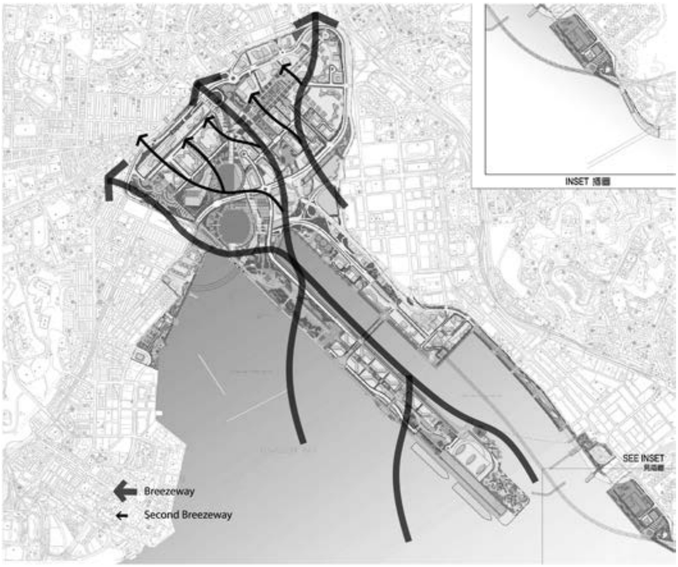


Figure 4.19. AVA was adopted in the re-development of the old Kai Tak airport. (Source: Author, adapted from PlanD, 2006)

(3) Building podia that occupy the entire site are discouraged.
(4) Extensive greening areas were planned; they are also linked from the waterfront to the inland areas.
(5) Extensive waterfront promenades were incorporated.
(6) Building heights were controlled.
(7) Roads were minimized, pedestrian walkways were emphasized.

Most of the urban air ventilation guidelines as in the HKPSG were incorporated. The plan was gazetted in 2012 (as the Kai Tak (kpa22) Outline Zoning Plan S/K22/4).

Another application of the AVA-TC06-01 is the HKSAR Government mandate that all land sales need to go through AVA so that appropriate land sale conditions may be incorporated into the land lease. For example, if an air path is deemed necessary to be incorporated across the project site, this will be marked and denoted as a non-building area (NBA) in the land lease. Project proponents need to observe this restriction when they design the buildings.

In addition, the HKSAR Government also requires all major public projects, including new development areas (NDAs) and public housing projects to go through AVA studies. The results of the study must be made public and be lodged with the Planning Department's AVA Register (PlanD, 2014). One example is the study leading to the design of the Hong Kong Government Headquarters buildings on the Tamar site (RWDI, 2007).

At the project design level, project proponents wishing to deviate from the established plan, such as by increasing the project's building height beyond what is allowed in the Outline Zoning Plan, must conduct AVA studies to demonstrate that the deviation does not cause unnecessary adverse impact to the site's urban air ventilation. The methodology is contained within AVA-TC06-01.

Lately, the AVA studies have also been incorporated into Hong Kong's building environmental assessment (BEAM+) system (BEAM, 2012). Under site aspect, credits are given if AVA studies have been conducted and the better design has been selected. Furthermore, AVA studies have also been incorporated into the Buildings Department of the HKSAR Government's Sustainable Building Design Practice Notes. (BD, 2011) Basically, if the project proponents cannot satisfy the prescriptive building permeability requirements, they have to demonstrate performance compliance based on AVA studies.

All in all, AVA has been with the construction industry in Hong Kong for almost 10 years now. Progresses towards a better urban air ventilation environment has been made, albeit slowly. The most crucial thing is that the industry and the general public accept the importance of air ventilation. The topic is now part of the planning and design process for government agencies, property developer communities and the planning and design professionals.

4.7 Beyond Wind

Urban thermal comfort is more than urban air ventilation; it is necessary to go beyond wind. In 2006, the Planning Department of the HKSAR Government initiated the urban climatic map (UCMap) study. The idea was to establish an information platform of the city's urban environment so as to provide an evidence basis for future planning (PlanD, 2012).

UCMap is not a new idea, as it originated in Germany in the 1980s (Ren *et al.*, 2010). It puts into map form urban climatic information and recommendations that planners may easily access. Two cities in Europe are leaders in UCMap for city planning: Stuttgart and Berlin (Stuttgart, 2014) (Berlin, 2014). In Asia, the metropolitan government of Tokyo started the city's UCMap in 2000 (TMG, 2005).

UCMaps have two key components. The scientific component is called the urban climatic analysis map (UC-AnMap) (Fig. 4.20), where morphological and climate data of the city are input and collated on the geographical information system (GIS). This component performs the calculations of UHI intensities, heat stress probability, wind availability, land surface characteristics, surface roughness, frontal area densities, greening extents, sky view factors, and so on of the urban areas of the city. The result is typically represented in

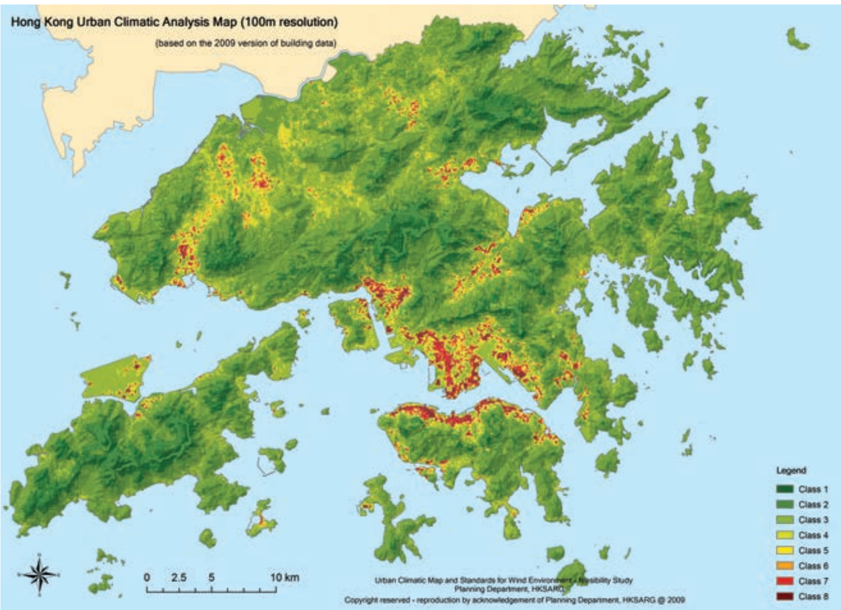


Figure 4.20. Hong Kong urban climatic analysis map. (Source: Author)

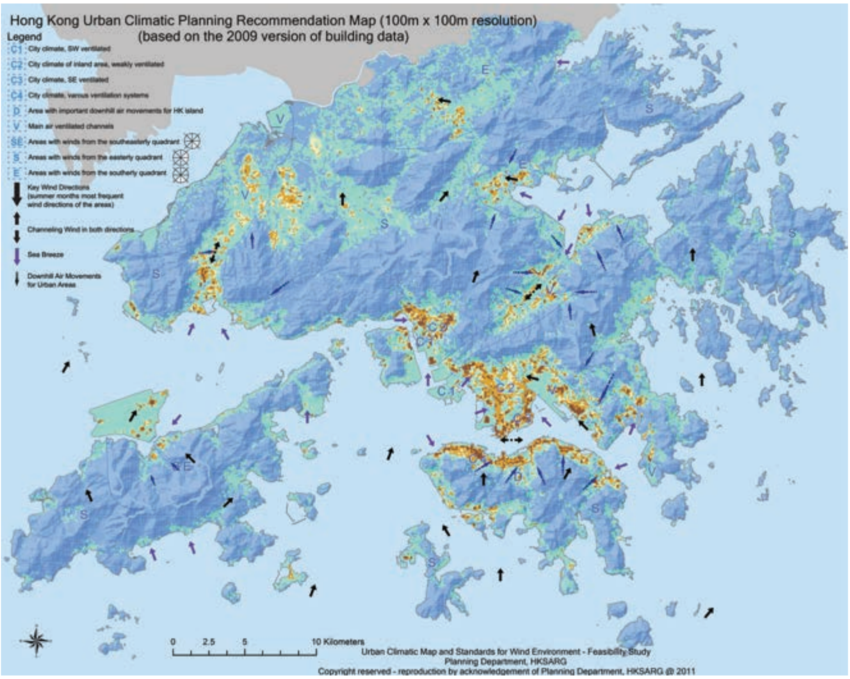


Figure 4.21. Hong Kong urban climatic planning recommendation map. (Source: Author)

terms of a bio-climatic summary based on human thermal comfort models, like PET. The color-coded UC-AnMap hence categorizes the scale and likelihood of undesirable urban situations that may need mitigation measures.

The planning component is called the urban climatic planning recommendation map (UC-ReMap) (Fig. 4.21). This is where the UC-AnMap will be used as the basis of discussion between the urban climatologists and the planners so that the understanding can be translated into planning actions. For example, if mitigation measures are desired, discussions on where, what width, what direction, what kind of building set back, what percentage of greenery, and so on, are needed. This will eventually be the work tool of the planners. The UC-ReMap should contain no scientific jargon. It should not contain any more information than the planners need for making decisions (Ng, 2012).

UCMaps provide a powerful visual tool to planners so that at the city and district scale of planning, the environmental parameters of the city may be better understood. Large-scale wind and air mass movements may be better appreciated and their benefits incorporated into the early planning stages. Homing into the city at the project and neighborhood level, given the background of a better city-scale urban environment, UCMaps provide the information needed for project proponents to better relate their design with its surroundings. In addition, UCMaps can also be the basis of impact assessment — especially heat stress related mortality (Goggins *et al.*, 2012; 2013).

4.8 Conclusion and the Road Ahead

The World Climate Conference 3 (WCC3, 2009), held in Geneva in 2008, provided the scientific backup to the United Nations Climate Change Conference in Copenhagen that produced the Copenhagen Accord. Never mind the political consequences, the important note to take is that for the first time in the long history of the World Climate Conference tradition (the first conference in 1979 resulted in the establishment of the Intergovernmental Panel on Climate Change (IPCC)) (IPCC, 2014a), the issue of urban climate was brought up under W8 climate and more sustainable cities. Two white papers were produced. The paper on needs led by Mills *et al.* (2010) highlighted the dire need for the scientific community to consolidate our knowledge for the service of the planning community. The need for climate-based planning, and the necessary methodologies of how to go about doing it, have been very clearly laid out. How to effect knowledge transfer is still a challenge. I quote from the paper:

(a) *Purpose: Climate knowledge should be integrated into planning and design to achieve distinct goals that have measurable targets against which the plan can be judged.*
(b) *Timing: Climatic analyses should be carried out at the very beginning of the design process before possible avenues are blocked off by uninformed decisions. Appropriate climatic strategies can*

rarely be applied retroactively to rectify errors made in the initial stages of the design.

(c) *Subsidiarity: In planning and design, the final design is a result of an optimizing process that involves different levels of planning. Establishing the benefits of a particular approach in general terms at the lowest level is of great benefit, but if the desired result can be achieved by several methods, then the method that can be applied as late in this process as possible should be preferred.*

(d) *Complexity: Architects and planners must synthesize information from many fields, of which urban climatology might be one. Any climate-based recommendation should define its goals and recognize that narrowly prescribed solutions can yield undesirable outcomes. For example, a design for pedestrian comfort is not necessarily compatible with one for building energy savings.*

(e) *Economic viability: Any recommendations of urban climatologists with respect to city planning are likely to have significant financial implications. Street width, for instance, is generally determined by the requirements of vehicular access, while building height reflects the desire to maximize the value of land. There is a real need for the development of a framework to assess the economic consequences of any recommended climatic strategy.*

(f) *Sustainability: Evaluating economic viability is a necessary but insufficient metric to assess a planning project and its climate consequences. Increasingly, climate considerations must incorporate other aspects of sustainable planning, and must account for social and environmental concerns.*

(g) *Clear and immediate benefits: In the absence of quantitative studies on the effect of proposed designs upon climate, decision-makers will downgrade the importance of climatic considerations. The field needs sufficiently accurate and reliable predictive tools, capable of testing different scenarios.*

(h) *Comprehensive approach to problem solving: Recommendations that are derived from a limited group of factors may be misleading if a critical factor is omitted. Computer modeling offers*

> *the opportunity for comprehensive analysis of the urban micro-climate. However, to be useful, models must address the issues that are foremost in the decision-maker's mind.*

Mills *et al.* further highlighted the challenges in terms of theory, science, communication, application and addressing sustainability (Mills *et al.*, 2010). Sustainability is about the future. As such, the story told so far on providing urban air ventilation and on addressing the planning issues of the urban climatic living environment is only the beginning. Given the inevitable occurrence of climate change and its global impact, as highlighted in the IPCC's latest framework report (IPCC, 2014b), urban living will face unprecedented challenges. The solution is not going to be scientific but will rest in politics. The actions needed are going to be drastic. What we have done so far is only touching the tip of an iceberg. The journey has just begun.

References

ASCE (1999). "Wind Tunnel Studies of Buildings and Structures", in Isyumov, N. (ed.) American Society of Civil Engineers Manuals of Practice (MOP) MOP 67.

AWES (2001). *Quality Assurance Manual for Wind-Engineering Studies of Buildings*, Australasian Wind Engineering Society, Australia.

BD (2011). "Sustainable Building Design Guidelines", *APP152 Practice Note for Authorized Persons, Registered Structural Engineers and Registered Geotechnical Engineers*, Buildings Department, Hong Kong SAR Government, Hong Kong. Available at http://www.bd.gov.hk/english/documents/pnap/APP/APP152.pdf, (accessed 26 Apr 2015).

BEAM (2012). *Building Environmental Assessment Method Plus for New Buildings [version 1.2]*, BEAM Society Ltd. and Hong Kong Green Building Council, Hong Kong. Available at http://www.beamsociety.org.hk/files/download/download-20130724174420.pdf (accessed 26 Apr 2015).

Berlin (2014). *Environmental Atlas*, Senate Department for Urban Development and the Environment, Berlin, Germany.

Cheng, V. and Ng, E. (2006). Thermal comfort in urban open spaces for Hong Kong, *Architectural Science Review*, **49**(3), 236–242.

Cheng, V., Ng, E., Chan, C. *et al.* (2010). Outdoor thermal comfort study in sub-tropical climate: a longitudinal study based in Hong Kong, *International Journal of Biometeorology*, **56**(1), 43–56.

Chun, C. and Tamura, A. (2005). Thermal comfort in urban transitional space, *Building and Environment*, **40**, 633–639.

de Dear, R.J. (2009). Revisiting an old hypothesis of human thermal perception: Alliesthesia, *Building Research and Information*, **39**(2), 108–117.

DevB (2006). *Air Ventilation Assessments*, Development Bureau, HKSAR Government, Hong Kong. Available at http://www.devb.gov.hk/filemanager/en/content_679/hplb-etwb-tc-01-06.pdf (accessed 26 Apr 2015).

Goggins, W.B., Chan, E.Y.Y., Ng, E. *et al.* (2012). Effect Modification of the Association between Short term Meteorological Factors and Mortality by Urban Heat Islands in Hong Kong, *PLoS ONE, 7*(6), e38551, doi:10.1371/journal.pone.0038551.

Goggins, W.B., Ren, C., Ng, E. *et al.* (2013). Effect Modification of the Association between Meteorological Variables and Mortality by Urban Climatic Conditions in a Tropical city: Kaohsiung, Taiwan, *Environmental Health Perspectives*, **12**, 59, doi:10.1186/1476-069X-12-59.

Heschong, L. (1979). *Thermal Delight in Architecture*, MIT Press. Cambridge, MA.

HKPSG (2014). "Chapter 11: Urban Design Guidelines", *Hong Kong Planning Standards and Guidelines*, HKSAR Government, Hong Kong. Available at http://www.pland.gov.hk/pland_en/tech_doc/hkpsg/full/ (accessed 26 Apr 2015).

HKGSAR (2007). *Kai Tak Planning Review*, HKSAR Government Development Bureau and Planning Department, Hong Kong. Available at http://www.pland.gov.hk/pland_en/p_study/prog_s/sek_09/website_chib5_eng/english/index_e.html (accessed 26 Apr 2015).

Höppe, P. (1999). The physiological equivalent temperature — a universal index for the biometeorological assessment of the thermal environment, *International Journal of Biometeorology*, **43**(2), 71–75.

IPCC (2014a). Intergovernmental Panel on Climate Change. Available at http://www.ipcc.ch/ (accessed 26 Apr 2015).

IPCC (2014b). IPCC Fifth Assessment Report (AR5). Available at http://www.ipcc.ch/report/ar5/, (accessed 26 Apr 2015).

Khedari, J., Yamtraipat, N., Pratintong, N. *et al.* (2000). Thailand ventilation comfort chart, *Energy and Buildings*, **32**, 245–249.

Kubota, T., Miura, M., Tominaga, Y. *et al.* (2008). Wind tunnel tests on the relationship between building density and pedestrian-level wind velocity: development of guidelines for realizing acceptable wind environment in residential neighbourhoods, *Building and Environment*, **43**(10), 1699–1708.

Mills, G., Cleugh, H., Emmanuel, R. *et al.* (2010). Climate information for improved planning and management of mega cities (Needs Perspective), *Procedia Environmental Sciences*, **1**, 228–246, doi:10.1016/j.proenv.2010.09.015.

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**(7), 1478–1488.

Ng, E. and Cheng, V. (2011). Urban human thermal comfort in hot and humid Hong Kong, *Energy and Building*, **55**, 51–65.

Ng, E., Yuan, C., Fung, J.C. *et al.* (2011). Improving the wind environment in high-density cities by understanding urban morphology and surface roughness: A study in Hong Kong, *Landscape and Urban Planning*, **101**(1), 59–74.

Ng, E. (2012). Towards a planning and practical understanding for the need of meteorological and climatic Information for the Design of High Density Cities — a case based study of Hong Kong, *International Journal of Climatology*, **32**, 582–598.

PlanD (2006). Kai Tak Planning Review, preliminary outline development plan, public consultation digest (3). Available at http://www.pland.gov.hk/pland_en/p_study/ prog_s/sek_09/website_chib5_eng/english/index.html (accessed 14 May 2015).

PlanD (2012). *Urban Climatic Map and Standards for Wind Environment*, Planning Department, HKSAR Government (produced by Chinese University of Hong Kong), Hong Kong. Available at http://www.pland.gov.hk/pland_en/p_study/prog_s/ucmapweb/index.htm (accessed 26 Apr 2015).

PlanD (2014). *Air Ventilation Assessment Register*, Planning Department HKSAR Government, Hong Kong. Available at http://www.pland.gov.hk/pland_en/info_serv/ava_register/government.html (accessed 26 Apr 2015).

Ren, C., Ng, E. and Katzschner, L. (2010). Urban climatic map studies: a review, *International Journal of Climatology*, **31**(15), 2213–2233.

RWDI (2007). "Air Ventilation Assessment Tamar Development Project Hong Kong", *Project Number: #07-1033A*, Rowan Williams Davies & Irwin Inc. Available at http://www.pland.gov.hk/pland_en/info_serv/ava_register/ProjInfo/AVRG74_AVA_FinalReport.pdf (accessed 26 Apr 2015).

Stuttgart (2014). *Urban Climate*, City of Stuttgart, Office for Environmental Protection, Section of Urban Climatology, Stuttgart, Germany. Available at http://www.stadtklima-stuttgart.de/index.php?climate_in_stuttgart (accessed 26 Apr 2015).

TMG (2005). Guidelines for Heat Island Control Measures, Bureau of the Environment, Tokyo Metropolitan Government, Tokyo, Japan. Available at http://www.kankyo.metro.tokyo.jp/en/attachement/heat_island.pdf (accessed 26 Apr 2015).

WCC3 (2009). http://www.wmo.int/wcc3/page_en.php (accessed 26 Apr 2015).

Yoshie, R., Tanaka, H., Shirasawa, T. *et al.* (2008). Experimental study on air ventilation in a built-up area with closely-packed high-rise building), *Journal of Environmental Engineering*, **627**, 661–667 (in Japanese).

Chapter 5

Vegetation and climate-sensitive public places

Denise H.S. Duarte

5.1 Role of Vegetation in High-Density Tropical Cities

Urban growth typically decreases space for green areas and urban environment creates obstacles to the planting of new trees. These include soil compaction, lack of space for roots, overhead (and underground) provision of services and the lack of adequate management of trees. Vegetation is scarce even in many tropical cities. There has often been a tendency to replace natural vegetation and permeable soils with impervious surfaces such as asphalt and concrete, which leads to more sensible than latent heat flux. The consequences of neglecting green and water infrastructure — factors that modulate urban climate — are evident: recurrent and severe flooding, excessive heating of urban surfaces, low air quality and increase in urban heating, even daytime urban heat islands (UHIs) in the tropics, among other factors. An increase in evaporation in urban areas needs an increase of vegetation and water surfaces, as well as rainwater retention (Emmanuel, 2005). The situation is worse in high-density cities, where land is scarce and there is little provision of space for the incorporation of urban greenery such as urban parks and landscaping. Land-use pressures and overheated property markets limit the potential for large-scale green infrastructure (Ong *et al.*, 2012). The integration of greenery in buildings and dense urban spaces faces many constraints (Chen and Wong, 2010), in spite of some cases of success, such as Singapore, with the adoption of Green Plot Ratio by local legislation (Ong *et al.*, 2002).

Concerning the dense and informal city, 29% of the global urban population (nearly 1 billion people) resides in informal settlements (Davis, 2007) without minimum conditions of health, sanitation, urban services and amenities. In Brazil, the resident population in informal settlements is 6% out of the over 190 million total population, i.e. more than 11 million people (IBGE, 2010), which corresponds to the population of city of São Paulo. In São Paulo, 1.6 million people live in slums in the almost 400,000 dwellings (São Paulo, 2010), under precarious conditions of solar access, ventilation and lack of public services.

Even so, one can identify many attempts to include green somehow even in very small areas spread all over the communities (Fig. 5.1).

Encompassing the formal and informal city, these small green areas could include the development of green walls, bio-diverse parks, community gardens, urban orchards, linear parks, parklets, rooftop terraces and gardens, and green enhancement of narrow streets, alleys and lanes. In addition, green areas can include the use of streets as effective public spaces for the pedestrians, even with a temporary character as for open markets, community celebrations or sports. Other transitional spaces, such as balconies and urban stairs can be used to add green in the spaces between buildings, public, semi-public or private, all of which are important from an urban and environment point of view, as effective spaces for urban life, adding green of either permanent or temporary character.

Four characteristics of cities contribute to raise temperatures: reduction in evaporative cooling, reabsorption of reflected radiation by the vertical surfaces of buildings/canyons, low surface reflectivity and generated heat. The two first can be directly mitigated through vegetation.

Planted areas in a city tend to reduce daytime maximum temperatures, reducing radiant exchange at the ground surface. The effect of vegetation on the atmospheric UHI is manifested not only indirectly, in the form of a reduction of sensible heat flux from the cooler

Figure 5.1. Inequalities in green distribution contrasting Paraisopolis (slum) with Morumbi (high-income neighborhood) in São Paulo, and local residents inclusion of green somehow in the community. In the last picture, according to the household, this is an individual attempt to feel closer to nature, using green PET bottles to build part of the house. (Sources: aerial view from L. Ferreira, 2010; from inside the community, E. Pizarro, 2013/2014)

surface, but also directly in the form of evaporative cooling. Most field studies support the argument that a lack of vegetation in the city would tend to result in elevated daytime air temperature, and concomitantly, that a large-scale planting campaign may lead to a reduction of the daytime UHI (Erell *et al.*, 2011).

From the microclimate point of view, the problem is not the size of the city itself, but rather the land occupation patterns, and not only high-density cities, because low-density areas can be even worse for urban warming. According to Stone (2012), extremely hot days in the most sprawling US cities are growing at more than twice the rate of the most compact cities. In the context of UHI measurement, areas of low population density may have a significant influence on heat island formation if they have extensive infrastructure development.

According to Wong and Chen (2009), the UHI effect can be understood as a conflict between buildings and the urban climate, and considering the positive impact of plants upon the conflict, a conceptual model was proposed by the authors to understand the interactions among the three critical components in the built environment: climate, buildings and plants. In order to uncover the benefits of greenery in a built environment, the microclimatic effects should be quantified. There are some possibilities to reduce ambient air temperature with plants: urban parks, road trees, landscape within the vicinity of buildings and rooftop gardens. In addition, the surface temperatures could be reduced with rooftop gardens or vertical landscaping.

Following Wong and Chen (2009), from the planning point of view, it can be found that smaller green areas strategically arranged or grouped around buildings should be largely promoted. This does not mean that large urban parks are not effective in terms of improving urban climate, but they are considered as a luxury to a heavily built-up environment, especially if rapid urbanization is experienced.

Besides, urban variables have an effect on the type, size and quality of green infrastructure. For example, urban densification and topography are important drivers of the availability and quality of urban green spaces. The road network and the buildings footprint in an area negatively contribute to the extent of green space (Davies *et al.*, 2008); this is why other forms of green structure have to be found.

In high-density cities, another possibility to be explored is the green infrastructure coupling with different approaches of on-street and off-street parking. Besides, the distribution and shared and mixed use of street network can add a green perspective to the road network system, concerning vegetation and water retention, for example. Green infrastructure can be valued as enhancing mobility, incentivizing walking, cycling and more energy efficient transport systems, such as the East London Green Grid or the Green Cycle Routes of Copenhagen, leading to a cohesive network of cycle routes and footpaths.

Another great physical benefit of green infrastructure is the energy consumption reduction in buildings, increasing the possibilities for free-running and mixed-mode operation, especially in tropical and sub-tropical climates. In order to evaluate the positive effect it is necessary to adopt appropriate green models, which in turn need to be appropriately coupled with building energy simulation (BES) systems. It is imperative that such exploration include green variables such as leaf area index (LAI), tree geometry and substrate characteristics together with heat and moisture exchanges, etc.

5.1.1 *Benefits of green infrastructure*

Bowler *et al.* (2010) applied a systematic review methodology to evaluate available evidence on whether greening interventions, such as tree planting or the creation of parks or green roofs, affect the air temperature of an urban area. Most studies investigated the air temperature within parks and beneath trees and are broadly supportive of the idea that green sites can be cooler than non-green sites. Meta-analysis was used to synthesize data on the cooling effect of parks and results show that, on average, a park was 0.94°C cooler in the day. Their meta-analysis initially focused on measurements during the day, for which there were most data available. However, this evidence is mostly based on observational data of existing green spaces.

Therefore, this hypothesis should continue to be tested through the appropriate monitoring of any urban greening programs. Monitoring should include collection of temperature data before and after implementation along with comparable 'control' non-green sites.

A crucial issue to the value of urban parks is whether a park has any effect on the temperature of the wider surrounding area (Bowler *et al.*, 2010). Here one must distinguish between the impact above and below the canopy level, and between mesoscale and microscale benefits. Below the canopy level, tree-shading effects are restricted to the limits of the park, and part of the effect of lowering air temperatures and increasing humidity can be extended to a few meters beyond the park, depending on wind direction and speed. Chen and Wong (2006) studied two large parks in Singapore and measured temperatures at increasing distance from the park up to approximately 500 m from the boundary. For both parks, temperatures gradually increased with increasing distance from the park boundary.

According to Jauregui (1990/91) thermal contrasts between a large park area (∼500 ha) and a nearby urban site in Mexico City showed large cooling rates in the green area, minimum temperatures were 3–4°C cooler in the park and its influence reached a distance approximately equal to the width of the park (2 km).

For small green sites in Tel Aviv, Israel, the cooling effect estimated by Shashua-Bar and Hoffmann (2000) was perceivable up to about 100 m in the streets branching out from the site and the cooling effect was found to be relatively small, about 0.5 K, out of an average cooling of about 3 K at noon.

Studies from Spronken-Smith and Oke (1998) in Vancouver, BC and Sacramento, CA during summer conditions adopted a combination of remotely sensed surface temperature and air temperature from a fixed station and mobile (car and bicycle) traverses to characterize the magnitude of park-induced coolness, the 'park cool island' (PCI) effect. Air temperature effects were smaller. In Vancouver, parks were typically 1–2°C — in ideal conditions almost 5°C — cooler than their surroundings. Larger PCI are possible in Sacramento, where irrigated greenspace can be 5–7°C cooler. The influence of parks on air temperatures appears to be restricted to a distance of about one park width, but these PCI are park edge effects and are subject to uncertainty.

Spronken-Smith and Oke (1998) conclude that the magnitude of thermal effects in parks will vary depending on the park type and size, whether it is irrigated, the nature of the surrounding land use and the macroscale climate. The nature of these controls has not been systematically studied. Relatively little seems to be known about the diurnal variation of park cooling or its energetic basis. Most studies come from cities with temperate climates whereas the most pressing applications are in tropical climates.

Previous studies also show the effects of different types of vegetation, particularly the difference between short vegetation, such as grass, and tree canopy cover. Shade from trees has been shown to be important for lowering temperatures; however, temperatures have also been shown to be lower in unshaded green sites or above short vegetation, which suggests evaporative cooling may also play a role. A key line of future research is to explicitly investigate the distance and size-dependence of the effects of green areas, allowing explicit bottom-up predictions of the effect of particular amounts and spatial arrangements of greening (Bowler *et al.*, 2010).

According to Spronken-Smith and Oke (1998) parks with substantial tree canopies have maximum PCI in the afternoon. Garden, multi-use and savannah type parks peak soon after sunset, while open grass parks have a maximum PCI near sunrise. These observations suggest that during the day trees may play an important role in establishing a cool park effect, through a combination of shade and evaporative cooling. At night, it appears that the surface geometry and moisture status of the park are important controls on surface cooling.

Giridharan *et al.* (2008) investigated the impact of on-site variables on the influence of vegetation in lowering outdoor temperature in the high-density Hong Kong, and concluded that merely introducing vegetation in high-rise high-density developments will not lead to an appreciable reduction of outdoor temperature. The introduction of vegetation will have to be carefully managed with other on-site variables such as sky view factor and altitude to achieve tangible results.

Any future research on the impact of vegetation on UHI in high-rise, high-density environments should incorporate sky and roof terrace gardens in the sample. Such studies could consider the combination of podium, intermediate levels (sky garden) and roof terrace gardens as necessary urban level changes to create better thermal comfort in high-rise, high-density settings. Future models should also take into account off-site variables such as immediate surrounding density and anthropogenic heat. The study concluded that increasing the tree cover from 25% to 40% in the pocket parks in coastal area residential developments of Hong Kong could reduce daytime UHI intensity by further 0.5°C. At night, blocking of long wave radiation by urban vegetation is marginal compared to the cooling effect created by plant biology, but this needs to be researched further.

Ng *et al.* (2012), studying the impact of green areas on thermal comfort in a high-density urban living environment such as Hong Kong, conducted measurements and parametric studies to investigate the preferred location, amount, and types of vegetation for urban planning. For a city such as Hong Kong, which has a high building-height-to-street-width (H/W) ratio, the study reveals that roof greening is ineffective for human thermal comfort near the ground. Trees are also suggested to be more effective than grass surfaces in cooling pedestrian areas. The authors concluded that the amount of tree planting needed to lower pedestrians level air temperature by around 1°C is approximately 33% of the urban area when the building coverage ratio is set to 44%, which is the average value in Hong Kong. On the other hand, it should be noted that neither planting trees or grass on rooftops nor planting grass on the ground is effective in cooling the pedestrian environment in high-rise, high-density urban Hong Kong. At best, they may serve to benefit by not further warming up the hot urban environment as compared to artificial materials. Building heights have an implication on the cooling benefits of planting on building tops. When the H/W ratio exceeds 1, the benefit of the cooling effects at grade is low. It is important therefore that greening and, more importantly, tree planting be positioned nearer to the level where human activities are concentrated.

Field measurements by Shashua-Bar and Hoffman (2004) showed that some tree-aligned streets and boulevards in the Tel Aviv area, Israel, had 1–2.5°C lower air temperatures than non-vegetated streets at the hottest part of the day, 3 p.m. Applying the simulation software ENVI-met[1] to the climate of Thessaloniki, Greece, Chatzidimitriou *et al.* (2005) found small temperature decreases for tree-aligned streets (less than 1°C), but up to 20°C lower surface temperatures and more than 40°C lower mean radiant temperatures. The cooling effect was found to increase with rising number of trees. In the hot dry climate of Ghardaia, Algeria, Ali-Toudert and Mayer (2007) found that shading trees could improve the thermal comfort in streets considerably. In another simulation study of different greening scenarios using ENVI-met in Rio de Janeiro, Brazil, Spangenberg (2004) found that an increased amount of urban green (tree cover of 30% of the ground and 100% green roofs) could nearly recreate the comfortable conditions of a natural forest.

Combining the mesoscale model BRAMS and the micro-scale model ENVI-met, Johansson *et al.* (2013) simulated the microclimate of six different urban tissues on a typical summer day in São Paulo. The simulated air temperature and relative humidity were similar in all areas, whereas both wind speed and mean radiant temperature varied greatly between and within the areas. Thermal comfort was especially poor in non-shaded areas; on the other hand, the bare-soil, wooded area with a complete cover of tree canopy was the most comfortable one. It was shown that street trees greatly improve the thermal comfort in built-up areas and with street trees, the difference between low-rise and high-rise areas diminished. The shade improved in the areas without vegetation, especially in the high-rise area; however, for areas with street trees the orientation has negligible importance.

Considering different values for LAI, which is an important vegetation biophysical parameter discussed later in this chapter, Shinzato and Duarte (2012) investigated the effect of tree density

[1] http://www.envi-met.com/

on air and surface temperature at pedestrian level in São Paulo. Based on LAI measurements at Ibirapuera Park, three LAI values (1, 3, 5) were selected for simulation in the microscale model ENVI-met as parametric scenarios. The model considers that LAI is known and leaf area density (LAD) can be calculated by integrating LAI values. Dense trees (LAI = 5) showed an average difference of 14.7°C for ground surface temperature between the green area and the street, as well as 10°C for trees with LAI = 3 and 5°C for trees with LAI = 1. Regarding air temperature, differences under dense trees (LAI = 5) and the street is up to 1.3°C, similar to the local temperature decrease registered in field surveys.

In São Paulo, the microclimates of a park, a square and a street canyon in the downtown were measured on a summer day. The aim was to study the effect of shading trees with different leaf densities on the microclimate and outdoor thermal comfort in public spaces. The field monitoring showed that the park was up to 2°C cooler than the square and the canyon. The effect of adding shading trees to the street canyon was simulated for the same day using ENVI-met. The simulations showed that incorporating street trees in the urban canyon had a limited cooling effect on the air temperature (up to 1.1°C), but led to a significant cooling of the street surface (up to 12°C) as well as a great reduction of the mean radiant temperature at pedestrian height (up to 24°C). Results show that among the three simulated cases, canyons covered with less dense (LAI = 1) and dense (LAI = 5) tree canopies have on average 0.5°C and 1.1°C lower air temperatures respectively than the base case without trees. Although the trees lowered the wind speed up to 45% of the maximum values, the thermal comfort was improved considerably as the physiologically equivalent temperature (PET) (Höppe, 1999) was reduced by up to 12°C (Spangenberg *et al.*, 2008).

Differences of these magnitudes in air and surface temperatures are perceived by the human body, and can affect positively the thermal comfort sensation in tropical and sub-tropical climates. Thermal sensation can be estimated with the application of comfort indices for open spaces, such as PET or TEP (temperature of equivalent perception) (Monteiro and Alucci, 2011), developed empirically for local conditions in São Paulo, which can drop about 10°C or more under tree shading.

In summary, we can conclude that the effect of vegetation on the thermal environment of its surrounding area seems to be small but still significant for urban microclimate and human comfort; we suggest that smaller green areas with sufficient intervals are preferable for effective cooling of the surroundings than a few larger green areas.

5.2 Energy Balance and Physical Properties of Vegetation

The presence of vegetation influences two mechanisms to counterbalance urban warming: shading and evapotranspiraton (Akbari *et al.*, 2001; Wong and Chen, 2009). To be more precise, vegetation mitigates urban warming not by cooling the air, but by warming the air less.

Trees can lead to a general improvement in air temperature, due to the combined effect of shade and evapotranspiration. Usually air temperature reductions from 1°C to 3°C can be achieved under the canopy in green areas, depending on the climate and soil conditions. The higher contrasts in cooling effects can be explained by the higher cooling effect of evapotranspiration due to drier climate conditions.

From the microclimate point of view, vegetation is important due to its energy balance properties. To assess the physical cooling effects of vegetation in urban microclimates, the interaction between soil, vegetation, and atmosphere must be understood, through coupled climate–vegetation dynamics (Bonan, 2010). Only this way can one answer apparently simple questions (that demand very complex interactions) such as:

- What is the magnitude of green effects in urban microclimate?
- How is the effect distributed spatially?
- How big is the area of influence of an urban park?
- How far from the green areas could the microclimatic benefits be felt?
- How to quantify the impact of shading, gap fraction, tree geometry and soil characteristics?

Typically, the availability of water and the resulting increase in evaporation result in lower surface temperatures. However, the effect of vegetation is quite complex, and varies with the type of plant, meteorological conditions and time of the day. Under certain conditions, an urban park may even be slightly warmer than the surrounding built-up area. Energy storage in plants, unlike that in hard surfaces, has two distinct components: (1) physical heat storage; (2) biochemical heat storage, because of photosynthesis and CO_2 exchange (Erell *et al.*, 2011).

The overall effect depends on the energy and water balance of vegetation, and energy and mass exchanges between vegetation and atmosphere have vegetation regulators associated with structure and physiological aspects. The evapotranspiration rate by plants is directly related to the quantity of stomata in the surface of leaves. Stomata are located on the surface of leaves that make the connection between the atmosphere and the interior of the plants. This is a consequence of the photosynthesis, since, during the day, the stomata are open to receive and eliminate CO_2, functioning as valves, thereby exposing the interior moisture (Oke, 1987).

Urban energetics are driven by a primary source of energy: solar radiation, complemented by long-wave radiation from green structures and other adjacent surfaces. Besides, latent heat exchange occurs not only as a result of condensation or evaporation at the ground surface, but to a large extent due to transpiration from plant leaves.

Shading and evapotranspiration depend on the canopy physical structure and on the interaction between soil, vegetation and atmosphere. Shading results from the attenuation of solar radiation under tree canopies, determined by tree geometry and density of leaves, which forms the basis for a large part of the indirect methods to characterize plant cover. The density of leaves is an indicator of gas exchange (oxygen and carbon dioxide) as well as the water vapor loss in transpiration.

Many of the ecological benefits of plants arise from their living processes. The intensity of these living processes is linked to greenery density, often expressed in terms of LAI. LAI is a dynamic parameter that indicates the growing rate of a plant, which results in widely varying LAI values across seasons. It is a notoriously indeterminate number, as the density of leaves differ from plant to plant within a particular species, from time to time during the plant's growth, and even from spot to spot throughout the plant's canopy during any particular measurement (Ong, 2015).

Different definitions of LAI were reviewed by Jonckheere *et al.* (2004), starting from Watson (1947) who defined LAI as one half of the total leaf area per unit ground surface area, a dimensionless variable (m^2/m^2). For Chen and Black (1992), LAI is half the total intercepting (non-projected) area per unit of ground surface area. Jonckheere *et al.* (2004) also noted that different definitions could result in significant differences between calculated LAI values.

LAI drives the within- and the below-canopy microclimates, determines canopy water interception, radiation extinction, and water and carbon gas exchange. LAI is a key parameter in models describing the exchange of fluxes of energy, mass (e.g. water and CO_2), and momentum between the surface and the planetary boundary layer.

LAI measures the amount of leaf material (photosynthetic tissue) in an ecosystem, which imposes important controls on photosynthesis, respiration, rain interception, and other processes that link vegetation to climate. Consequently, LAI appears as a key variable in many models describing vegetation–atmosphere interactions, particularly with respect to the carbon and water cycles. The interest in information on LAI distribution and changes has grown substantially in recent decades, due to its intrinsic importance and the emerging capability for LAI estimation over large areas using satellite measurements (FAO, 2009).

The significance of employing LAI is that it is a common denominator in many of the ecological effects of plants. The key to understanding this lies in first understanding the role of LAI in the interception of sunlight through a plant canopy. The amount of sunlight intercepted by a canopy is mathematically represented by Beer Lambert's Law, which models light transmission through the canopy in terms of an exponential function linked to LAI and k, the extinction coefficient of the canopy. The value of k depends on several factors, including leaf transparency and the angle of the leaf to the sunlight, or radiant flux. The product $k{\cdot}\mathrm{LAI}$ is applied to calculate the rate of energy flow through the foliage. This exponential relationship may be regarded as a general equation that describes the absorption of a flux (energy — e.g. light, wind, rain) through a permeable medium (the canopy). This not only describes the amount of sunlight that penetrates through the canopy, but also enables the calculation of the cooling effect of plants through transpiration. The amount of transpiration at the leaf level is complex and dependent on several factors, but can be reduced in terms of environmental factors to the water potential of the air. Most of the heat energy used by the plant is absorbed through transpiration as it involves the latent heat of evaporation of water which is around six times the energy required to heat the same amount of water from 0°C to boiling point. A much smaller amount of energy is absorbed by the plant mass so that, in general, the resultant temperature on the leaf surface is around air temperature (Ong, 2015).

Plant canopies have a vertical gradient of sunlight related to the amount of leaves. The sunlight striking an individual leaf is absorbed, reflected, or transmitted by the leaf. As the canopy becomes denser with leaves, more solar radiation is absorbed or reflected and less is transmitted deeper into the canopy. A simple model of radiative transfer shows that solar radiation decreases as an exponential function of LAI. The extinction coefficient depends in part on leaf orientation and solar zenith angle. These affect the angle at which the solar beam strikes a leaf, and greatest radiation per unit area is received when the beam is perpendicular to a surface. Just to have a general idea, a typical LAI for a productive forest is 4–6 (Bonan, 2010). Typical LAI values are shown in Tables 5.1 and 5.2; values were raised adopting two different techniques, detailed later in this chapter.

LAI is not the only variable that determines the plant's responses to the environment. Other factors like orientation of leaves and canopy geometry affect radiation extinction (Jones, 2014) and

Table 5.1. LAI values using the plant canopy analyzer technique (LAI 2000 Plant Canopy Analyser, Li-Cor). (Source: data compiled by Shinzato for this book chapter, 2015)

Green Typologies	LAI	References
Shrubs in Singapore	3.5–4.0	Yok and Sia (2010)
Isolate palm tree in Singapore	2.5–4.0	Yok and Sia (2010)
Isolate tree in Germany	4.5 (average value)	Barclay *et al.* (2000)
Isolate evergreen trees in Singapore	2.5–4.0	Yok and Sia (2010)
Evergreen park in São Paulo Brazil	2.5 (average value)	Shinzato *et al.* (2013)
Eucalypt forest in Brazil	2.86 (average value)	Xavier *et al.* (2002)
Eucalypt forest in Kerala, India	2.75 (average value)	Kallarackal and Somen (1997)
Eucalypt forest in Australia	4.1 (average value)	Vertessy *et al.* (1995)
Coniferous forest in Canada	3.32–4.06	Barclay *et al.* (2000)
Coniferous forest in Canada	3.1–6.7	Chen *et al.* (2006)

Table 5.2. LAI values using the hemispherical photography technique. (Source: data compiled by Shinzato for this book chapter, 2015)

Green Typologies	LAI	References
Crops (maize) in France	0.4–2.9	Demarez *et al.* (2008)
Crops (wheat) in France	0.2–3.4	Demarez *et al.* (2008)
Eucalypt forest in Australia	4.4 (average value)	Vertessy *et al.* (1995)
Coniferous forest in Canada	3.2–4.8	Zhang *et al.* (2005)
Coniferous forest in Canada	3.5–4.0	Chen *et al.* (2006)
Evergreen park in São Paulo, Brazil	2.1 (average value)	Shinzato *et al.* (2013)
Tropical forest in Sumatra. Indonesia	3.9–6.1	Trichon *et al.* (1998)
Tropical forest in Borneo, SE Asia	4.8–6.8	Kumagai *et al.* (2004)
Amazon rainforest in Brazil	3.6–6.6	Aragão *et al.* (2005)

consequently the impacts on microclimate. Besides the tree itself, the resultant microclimate depends on the surrounding environment, built and unbuilt, hard or green, considering the interactions of soil, vegetation and atmosphere.

5.3 Measurement and Modeling of Green Infrastructure

5.3.1 *Green models*

In the meteorological field few urban energy balance models incorporate explicitly the vegetation in the urban landscape in order to model the very local interactions (Lemonsu *et al.*, 2012). One of these models is the vegetated urban canopy model (VUCM) (Lee and Park, 2008), which takes into account the presence and effects of vegetation in the radiative, energetic and dynamic calculations. Good performances were obtained by evaluating the model for Vancouver and Marseille field experiments. VUCM is an urban canopy model developed for mesoscale meteorological and environmental modeling. The urban geometry is composed of simple homogeneous buildings characterized by the canyon aspect ratio (H/W) as well as the canyon vegetation characterized by the leaf aspect ratio and leaf area density profile.

More recently a green version of town energy budget (TEB) (Masson, 2000), an urban canopy model, has been developed (TEB-Veg) (Lemonsu *et al.*, 2012). Vegetation is directly included inside the canyon, allowing shadowing of grass by buildings. The surface exchanges over vegetation are integrated in order to account for interactions between natural and built-up covers, making possible to plug and use any vegetation scheme. It is first based on new radiation calculations for a canyon composed of a portion of road and garden. Orientation of the road and distinction of the thermal evolution of the two walls are also introduced in the model. This approach takes into account the shadow effects for gardens. The surface exchanges between vegetation and atmosphere are then calculated by considering the real short- and long-wave radiation received by gardens, as well as microclimatic conditions (temperature, humidity and wind) within the canyon instead of those above the top of the canopy. Inversely, the microclimate within the canyon is resolved by including the contributions from gardens in heat, moisture and momentum. Results demonstrate the value of an explicit coupling between impervious covers and vegetation for mixed urban environments that include a significant portion of green areas.

New developments improved the first version by taking into account other types of urban vegetation. Besides parametrization dedicated to low vegetation in urban canyons (Lemonsu *et al.*, 2012) the TEB-Veg version now includes vegetated roofs (de Munck *et al.*, 2013), a GREENROOF module including hydrological and energetic performances. Ongoing studies of Redon *et al.* (2014) on thermo-radiative and aerodynamic effects of street trees interacting with buildings are developing a parametrization in TEB-Veg, from the scale of the neighborhood to the scale of the city.

Following the cluster thermal time constant (CTTC) model (Swaid and Hoffman, 1990), Shashua-Bar and Hoffman (2002, 2004) proposed a Green CTTC model, including thermal effects of shade trees in the CTTC analytical model, derived from solar radiation exchange. This model is capable of investigating the climatic impact of trees on alternative urban design proposals. In the CTTC model, the predicted air temperature of a cluster is calculated through the contribution of the heat received from external sources. The cluster as defined in the model is an enclosure of open space between buildings such as urban streets, courtyards, squares and wooded green sites. The microclimate effects relate particularly to the cooling of the air in the presence of trees during daytime in summer. Using an energy balance approach, the thermal process is obtained mainly through changes in the insolation of the urban open space, expressed by: (1) reduction of the solar gain due to obstruction of the radiation by the tree canopy; (2) the energy consumption for evapotranspiration in the tree canopy; and (3) the change in the heat stored in the vegetation zone, which in daytime is expressed in raising the leaves' surface temperature.

An international comparison project, carried out in two phases, evaluated 32 urban land surface schemes, developed with different approaches. To model the exchanges for an urban environment, land surface models (LSMs) range from a relatively simple representation of the urban environment as an impervious slab to models that take into account the 3D geometry of buildings with varying heights and material characteristics. The phase 1 site, an industrial area in Vancouver, BC, had a much lower plan area fraction of vegetation than the phase 2 site, in Preston, suburban Melbourne, Australia. Conclusions show that whether or not vegetation cover is taken into account significantly impacts model performance, indicating that work needs to be done to improve simulations of latent flux (Grimmond *et al.*, 2010; 2011).

These mesoscale meteorological models bring huge advances, but they are still far from architects and urban planners. As pointed out by Wong *et al.* (2011), it is also rather difficult for the planners to attempt to design without engaging the urban climate scientists. Current priorities placed on sustainable urban development have encouraged urban planners to examine the various parameters of urban climate modeling and incorporate them into planning and design efforts. But while they may understand the importance of interactions between urban morphology and urban microclimate condition, they lack basic knowledge of urban climatology. Engaging urban climate scientists to conduct assessments and provide feedback has helped inform design and planning efforts, but to date the design process has been largely decoupled from the impact assessment and analysis process.

To overcome this gap, Wong *et al.* (2011) proposed a user-friendly urban design platform, aiming to generate an urban thermal comfort map where temperature, wind and solar radiation exposure layers are analyzed together on a GIS platform. Planners could then analyze expected comfort levels and make changes in the design at the locations where it is uncomfortable.

A simpler approach in exploratory studies in the urban planning field is based on simple or multiple regression analysis attempting to understand the phenomena — some of which include green variables. Regression models usually link microclimatic variables to urban variables, such as plot ratio, site coverage, percentage of green (usually described as the horizontal projection of tree canopies) and water surfaces. One of these studies was carried out for a continental tropical climate in Brazil, under very severe warm conditions. Based on the correlations an empirical indicator was proposed (Duarte and Serra, 2003; Duarte, 2010), in order to guide the necessary counterbalance between built-up and green areas to ameliorate urban microclimate.

Giridharan *et al.* (2008) adopted a multiple regression technique encompassing six critical on-site variables: surface albedo, sky view factor, altitude, shrub cover, tree cover and average height to floor area ratio, to carry out analysis in five data sets for high-rise, high-density residential developments of coastal Hong Kong, aiming to evaluate the vegetation influence on lowering the outdoor temperature. The tree or shrub cover indicated in this study is the visually projected foliage area of tree or shrub cover on the horizontal plane and expressed as a percentage of a $1000\,\text{m}^2$ area surrounding the measurement points.

Based on multiple regression analysis, Wong and Jusuf (2008a, 2008b), and Jusuf and Wong (2009) proposed an empirical model, screening tool for estate environment and evaluation (STEVE), from an architecture and urban planning point of view. Initially integrated as a plug-in into ESRI®ArcGIS Desktop, the current version uses Trimble Sketch-up, aiming to bridge the gap between complex prediction model and urban planners (Jusuf *et al.*, 2014). STEVE is a web application that calculates the minimum, average and maximum air temperature of a point of interest in the existing condition and future condition. It is possible to change the amount of vegetation, hard surfaces and buildings and subsequently calculate the predicted air temperature. When used together with GIS, temperature maps can be generated and the hot spots can be identified, enabling applications for architects, urban planners and government bodies, e.g. using building heat gain as a criterion in Singapore Greenmark assessment.[2]

The independent variables of STEVE can be categorized into (Jusuf and Wong, 2009):

1. Climate predictors: daily minimum (Ref T_{min}), average (Ref T_{avg}) and maximum (Ref T_{max}) temperature at a reference point;

[2] http://www.stevetool.com/

average of daily solar radiation (SOLAR). For the SOLAR predictor, average of daily solar radiation total ($\mathrm{SOLAR_{total}}$) was used in T_{avg} models, while average of solar radiation maximum of the day ($\mathrm{SOLAR_{max}}$) was used in the T_{max} model. SOLAR predictor is not applicable for the T_{min} model.

2. Urban morphology predictors: percentage of pavement area over $R = 50\,\mathrm{m}$ surface area (PAVE), average height to building area ratio (HBDG), total wall surface area (WALL), green plot ratio (GnPR), sky view factor (SVF) and average surface albedo (ALB). Wind speed, one of the most common variables, was excluded in the model development, since the models focus on calm day conditions.

Among the previous approaches, many studies on the impact of green in urban microclimate were made possible with ENVI-met (Bruse and Fleer, 1998), which had the initial versions designed in 1994. ENVI-met is one of the most promising micrometeorological models closer to urban planning applications, especially in the current version, ENVI-met V4.[3] However, the use of the model requires some knowledge of micrometeorology and can be computer-resource-intensive, depending on the simulated area and urban heterogeneity.

The ENVI-met is a 3D non-hydrostatic model for the simulation of surface–plant–air interactions not only for but also especially inside urban environments, with an advanced approach to plant–atmosphere interactions. ENVI-met is one of the few models that seeks to describe the major climate processes acting in the urban environment, including turbulence, turbulent transport of sensible and latent heat, radiation fluxes within the urban structures and the influence of vegetation. Based on the position of the sun, urban geometry, vegetation, soil and various construction materials, the model simulates aerodynamics, thermodynamics and the radiation balance in complex urban structures at 0.5–10 m resolution, by solving thermodynamic and plant physiological equations (Bruse; Fleer, 1998; Huttner, 2012). It has a typical time frame of 24 h to 48 h with a

[3] http://www.model.envi-met.com

time step of 10 s at maximum. This resolution allows the analysis of small-scale interactions between individual buildings, surfaces and plants. It considers LAD instead of LAI to calculate plants physiology. The model considers that LAI is known and LAD can be calculated by integrating LAI values (Jonckheere *et al.*, 2004).

Concerning the evaluation of shadowing effect of plants, ENVI-met considers vegetation as a turbid medium and calculates the transmittance of vegetation as a function of the optical path of solar beam through leaves and the LAI (Yang *et al.*, 2013). Advances in the green module ALBERO were presented in Version 4, recently released in a preview phase.

In ENVI-met V4, the forcing feature has been incorporated and it is now possible to define the diurnal variation of the atmospheric boundary conditions and the incoming radiation. Simple forcing allows temperature and humidity profiles to be incorporated in 24 hourly values. It also allows developing of much more detailed weather scenarios for testing purposes and producing results that are in good accordance with field measurements.

Among several features, the model calculation includes 3D representation of vegetation, including dynamic water-balance modeling of the individual species. ENVI-met supports simple vertical plants, but also allows complex 3D vegetation geometries like large trees. All plants are treated as individual species with an integrated water balance control and heat and water stress reaction concept. The temperature of the leaves is calculated by solving the energy balance of the leaf surface with respect to the actual meteorological and plant physiological conditions for each grid box of the plant canopy. Among other factors, the health status of the plant and water supply by the soil regulate the plants transpiration rate and thereby the leaf temperature.

ENVI-met uses a sophisticated model to simulate the stomata behavior of the vegetation in response to microclimate, CO_2 availability and water stress level. Vegetation interacts in various ways with the environment: heat and vapor are exchanged between the plants leaves and the atmosphere. Transpired water will be, if possible, extracted out of the soil's hydraulic model using the plant root distribution. A complex ray tracing algorithm is used to analyze the plants' impact on solar radiation (shadow casting) and on long-wave radiation exchange (thermal shielding). The effects of vegetation are included as drag forces in the wind field. The effect of vegetation is considered on all radiative fluxes. Building walls and roofs mainly act as surfaces interchanging heat with the atmosphere, but can also act as humidity sources if façade or rooftop greening is applied.[4]

Even though it is being used in different climates with good results, calibration with local microclimate and vegetation measurements are needed to better understand climate-related issues and get more confidence in the results.

ENVI-met V4 can also make a rough estimation for the energy performance of a building. However, such estimation would be suitable for the conceptual design of buildings as its main analyzing domain is focused on outdoor (Yang *et al.*, 2013). Additional model outputs include dynamic climate data along building façades and roofs, energy exchange at building canvas and thermodynamics of building walls. ENVI-met dynamically calculates the development of the building indoor temperature as a result of the incoming and outgoing fluxes through the associated wall and roof segments. This BES is executed parallel to the outdoor microclimate simulation for each building in the model domain, so that a constant feedback between the outdoor and indoor climate conditions and of the interactions between buildings is provided. The recent version allows an initial zoning model to define building sections and thermal zones.[5]

Another approach is to couple ENVI-met with BES models, such as Energy Plus on a coupling platform building controls virtual test bed (BCTVB). This one-way coupling simulation with no data feedback could benefit the continuous development of both models. However, given the computational costs of ENVI-met it is necessary to choose an appropriate model resolution according to the research

[4] http://www.model.envi-met.com
[5] idem

objectives or the design stages, models disparities of the numerical schemes and the differences in the physical models (Yang *et al.*, 2013).

Other efforts to incorporate greenery in BES models are beginning to emerge, truly incorporating green properties or trying to emulate the green effect mainly in roofs and walls. An example of the former is a physically based model of the energy balance of a vegetated rooftop integrated into Energy Plus. This module includes green roof design options including growing media properties and depth, and vegetation characteristics such as plant type, height and leaf area index (Sailor, 2008).

The model accounts for long-wave and short-wave radiative exchange within the plant canopy, plant canopy effects on convective heat transfer, evapotranspiration from the soil and plants, and heat conduction (and storage) in the soil layer. The ability to track moisture-dependent thermal properties is not implemented yet due to stability issues in the conduction transfer function (CTF) scheme, but is under development for use with the finite difference solution scheme made available in Energy Plus starting in version 2. The user can specify various aspects of the green roof construction including growing media depth, thermal properties, plant canopy density, plant height, stomatal conductance (ability to transpire moisture), and soil moisture conditions (including irrigation). The model formulation includes: (1) simplified moisture balance that allows precipitation, irrigation, and moisture transport between two soil layers (top and root zone); (2) soil and plant canopy energy balance; (3) soil surface and foliage temperature equations are solved simultaneously each time step, inverting the CTF to extract heat flux information for the energy balance calculation (EnergyPlus, 2014).

Attempts to emulate the green effect without considering green properties themselves include changes in albedo, or estimated R-values for green roofs based on *in situ* measurements. Wong *et al.* (2003) used DOE-2 to simulate the impact of rooftop garden on energy consumption of buildings, combining measured field data to calculate plants thermal resistance in three types of vegetation: turfing, shrubs and trees. The estimation of equivalent R-values was based on data collected in field measurements on a rooftop garden of a low-rise commercial building in Singapore.

Later, Wong *et al.* (2007) used TAS — thermal analysis software — (EDSL) to evaluate the performance of a rooftop garden in cooling energy savings for buildings, inputting the R-values calculated previously for the same vegetation types, base on *in situ* measurements as well.

5.3.2 *LAI measurement techniques and instrumentation*

There are two main procedures to obtain LAI: direct and indirect methods. The first group measures leaf area in a direct way, while the second group derives LAI from more easily measurable parameters in terms of time, workload and technology. Direct methods are implemented as calibration tools for indirect measurement techniques mainly, because they are extremely time-consuming and therefore making large-scale implementation only marginally feasible (Jonckheere *et al.*, 2004; Gower *et al.*, 1999; Jones, 2014).

Indirect methods in which leaf area is inferred from observations of another variable are generally faster and amenable to automation, and thereby allow a larger spatial sample to be obtained. For reasons of convenience, when compared to the direct methods, they are becoming more and more important. Indirect methods of estimating LAI *in situ* can be divided in two categories: (1) indirect contact LAI measurements; and (2) indirect non-contact measurements. These are ground-based measurements that usually integrate over one single stand only (Jonckheere *et al.*, 2004).

Optical methods are indirect non-contact methods and are more commonly implemented. They are based on the measurement of light transmission through canopies. These methods apply the Beer–Lambert's law, taking into account that the total amount of radiation intercepted by a canopy layer depends on incident irradiance, canopy structure and optical properties. It involves ground-based measurement of total, direct and/or diffuse radiation transmittance to the forest floor (Jonckheere *et al.*, 2004).

The hemispherical measurement of light transmission through canopies can be derived from hemispheric photography or hand-held sensors. These methods can be divided into two groups, depending on whether they measure gap fraction distribution (proportion of area patches illuminated by direct sunlight) or gap size distribution (the size distribution of the patches). The instruments provide data that represent LAI distribution at a point location, along a line, or over an area, as a hemispherical photograph (FAO, 2009).

For gap fraction distribution, which is the fraction of view in some direction from beneath a canopy that is not blocked by foliage, existing instruments employ canopy image analysis techniques or differential light measurements above and below the canopy. The maximum measurable LAI is generally lower for these devices measuring gap fraction than the one assessed via direct methods, and reaches a saturation level at LAI ≈ 5. The likely cause is gap fraction saturation as LAI approaches 5–6. A comprehensive survey comparing direct and indirect measures of LAI is presented in Gower *et al.* (1999).

For gap size distribution, available instruments measure the dimensions of individual surface patches that are directly illuminated. Analytical procedures and supporting measurements are employed to convert the measurements into LAI. Hemispherical photography is one such technique. Among sensors, some marketed instruments available are from Accupar, Demon and Li-Cor Plant Canopy Analyzer that calculate LAI by comparing differential light measurements above and below canopy.

The indirect non-contact measurements do not distinguish photosynthetically active leaf tissue from other plant elements such as stem, branches or flowers, and corrections are therefore required. Another important complicating factor is the clumping which leads to LAI underestimation; correction methods have also been developed for this effect (Weiss *et al.*, 2004; Jonckheere *et al.*, 2004).

Although optical devices are often used to estimate LAI, it is quantitatively derived from the gap fraction and a model of leaf angle distribution; gap fraction is the basic measurement of these optical instruments and an inversion of gap fraction to LAI is another pressing issue in indirect optical LAI determination (Jonckheere *et al.*, 2005). Most instruments based on gap fraction assess the effective LAI under the assumption of random spatial distribution of leaves, which is not valid for all cases, and underestimate LAI when foliage in the canopy is non-randomly distributed (i.e. clumped). Chen and Black (1992) used the term *effective LAI* to describe LAI estimates derived optically. This nomenclature seems most appropriate because it recognizes that conventional inversion models are incapable of measuring the surface area contributed solely by green leafy material, and that they are unable to compensate for the non-random positioning of canopy elements (Jonckheere *et al.*, 2004).

Hemispherical canopy photography is another technique for studying plant canopies using photographs captured through a hemispherical (fisheye) lens from beneath the canopy (oriented towards zenith) or placed above the canopy for downward looking. Furthermore, the use of a fisheye lens allows the gap fraction to be evaluated in all viewing directions, which increases the accuracy of the derived LAI, and there is a potential to characterize the azimuthal distribution of the foliage and the departure to non-random leaf arrangement. In addition, it is also possible to derive estimates of the LAI for canopies growing on sloppy terrains (Jonckheere *et al.*, 2005). Firstly, the camera and lens are calibrated to define the optical center and the projection function. Then, each image is pre-processed in the model. The pixel brightness values for the blue band are extracted from each RGB image to achieve maximum contrast between leaf and sky, because absorption of leafy materials is maximal and sky scattering tends to be highest in that band (Jonckheere *et al.*, 2005; Gonsamo and Pellikka, 2009). Additional procedures must be applied in order to identify the optimal brightness threshold and distinguish vegetation from sky (Weiss, 2010).

In summary, the various *in situ* LAI methods and results obtained have been described in peer-reviewed literature, and various intercomparison tests have been performed. The individual methods have specific strengths and weaknesses, and therefore are more applicable under some circumstances than others are. Although consensus seems to exist on the usefulness and applicability of the various approaches, no standards have been defined or accepted; however, common guidelines have often been developed and used by research teams collaborating in larger research programs in various countries (FAO, 2009).

Each system has its specific measuring details and the choice has to consider the local conditions for the studies. Plant canopy analyzers are more suitable for individual trees, whereas the hemispherical photographs are more suitable for a dense arrangement of trees as they evaluate an average LAI for a determined area, but not for a single tree. Another fact is that, even with the restricting caps overestimation can be found using Li-Cor canopy analyser when compared to the hemispherical photography, as it considers not only leaves but also other elements such as branches and trunk (Shinzato and Duarte, 2013).

Besides the optical methods referred above, remote sensing techniques can be adopted. The sensors register spectral differences between vegetation and soil, expressed, for instance, by the normalized difference vegetation index (NDVI) — spectral reflectance differences between red and near infrared — that can be used as a metric of green cover or to estimate the LAI (Jones, 2014).

When LAI is retrieved from remote sensing measurements, by inverting a radiation transfer model, its value corresponds to an effective value linked to the particular spatial resolution of those measurements. The conversion of geometrical measurements to effective values becomes an essential step and requires additional information about the structure and architecture of the canopy, e.g. gap size distributions, at the appropriate spatial resolutions (FAO, 2009).

Due to the spatial and temporal variability of LAI, the information required for climate change purposes can only be obtained through measurements by satellite optical sensors. Experience accumulated over the last decade shows that sensors featuring at least one spectral band in the blue domain (in addition to the usual red and near-infrared) yield much higher quality products because they allow for more accurate atmospheric corrections (FAO, 2009). As spatial resolution varies across satellites bands (spatial sampling of about 1 km or more), this technique is usually suitable for large areas, but is unable to infer LAI for single urban trees or even small urban parks.

5.4 Case Study: Green Infrastructure Benefits to a Megacity (São Paulo)

The recently constituted Brazilian Panel on Climate Change (PBMC) estimates that Brazil's climate will be warmer in the coming decades, with gradual and variable average temperature increase in all regions between 1°C and 6°C by 2100, compared to the recorded temperature at the end of 20$^{\text{th}}$ century (PBMC, 2013a; 2013b; 2013c). Brazil has its own voluntary commitments for emission reductions, as part of the National Policies for Climate Change, but adaptation measures for urban areas are still missing, and some local research groups are investigating this, aiming to support the review of the National Plan for Climate Change. Land use as a climate change mitigation measure, especially in urban areas, is underexplored. In this scenario, cities need to be more resilient and, for that, adaptation is crucial.

The PBMC is especially worried about the fast pace of vegetation suppression in São Paulo, both in the interspace of buildings as well as in the outskirts of the city. Megacities like São Paulo are vulnerable to global warming and local warming effects, driven by urbanization. According to PBMC (2013a, 2013b, 2013c) besides mean temperature warming, an increase of extreme events is expected in the future.

São Paulo is located in the Southeast region of Brazil, at 23° 32′ S, 46° 37′ W, 60 km from the sea. The altitude varies between 720 m and 850 m. The climate is sub-tropical (Köppen classification = Cfa) with mild temperatures. The city experiences hot, humid summers, with air temperatures varying between 22°C and 30°C, and mild winters with temperatures between 10°C and 22°C. On average, precipitation is around 1400 mm, unevenly distributed throughout the year, with rainy months in December, January, February and March and drier months in June, July and August, when thermal inversion occurs frequently (Fig. 5.2).

Based on historical data from WMO 83004, a meteorological station (located inside a park in Água Funda neighborhood in Southern

Figure 5.2. São Paulo — two climate aspects seen from a commercial high-rise, looking south; on the left, thermal inversion during the dry season in winter, early in the morning, July, 2012, and on the right, a storm approaching over the same area (Photos: J. Calsinski).

São Paulo, IAG-USP)[6] estimates the average maximum temperature rise was 1.8°C between 1933 and 2014, and the average minimum temperature rise 2.2°C in the same period. All months in 2014 had monthly mean temperatures above the historical averages, highlighting the high temperatures and the severe drought. During summer, January and February presented temperatures above those observed in decades and relative humidity values below those historically found. Whilst the historical climatological averages for these months were 21.6°C and 21.8°C respectively, the mean values recorded in 2014 were 24.2°C and 24.3°C. January 2014 was 2.2°C higher than expected, while February 2014 was 1.9°C higher than the historical average, both with maximum temperatures of 36.1°C, the highest mean temperatures since the meteorological station recordings started in 1933, surpassed only in January 2015, with 36.2°C. The absolute maximum ever registered was 37.2°C in October 2014. The same month had the maximum thermal amplitude of 20.7°C, on 12 October, with the minimum of 15.1°C and maximum 35.8°C. Also in

[6] The meteorological station IAG/USP is located at Parque Estadual das Fontes do Ipiranga (previously Parque do Estado), Água Funda neighbourhood, São Paulo, latitude 23,6512°S, longitude 46,6224°W, altitude 799,2m. Available at http://www.estacao.iag.usp.br/Boletins/2014.pdf, accessed May 3, 2015.

2014, another record was broken: there were 109 days with temperatures equal or higher than 30°C (whilst the average is 47 days). While January and February are generally characterized by high rainfall amount and an average relative humidity of 83%, the first two months in 2014 had lower precipitation rates and recorded lower values of relative humidity, 75% and 73% respectively (IAG/USP, 2014).

São Paulo is a sprawling megacity with 39 municipalities, currently the fourth biggest in the world, housing the same population as Mexico City and Mumbai, after Tokyo, the biggest, Delhi, the second and Shangai, the third. With more than 21 million inhabitants (UN/DESA, 2014) São Paulo is characterised by a heterogeneous urban structure, caused by the rapid growth of the city during the 20th century. High-rises are found everywhere in the city and contrast with poor informal settlements, spread all over the metropolitan area (Figs. 5.3–5.5).

In general, the city of São Paulo does not have a high-built density since its average plot ratio is 1. Higher values of up to 5 can be found in districts located in central areas, but higher population density occurs in peripheral districts, thus explaining a phenomenon quite pronounced in recent decades: dispersion of population. Although São Paulo's average population density of 74 inhab/ha (IBGE, 2010) is similar to many others in the world, its densest district is one of the lowest (only 279 inhab/ha). Some slums may have a population density higher than 1000 inhab/ha without any urban quality, but similar values could be reached in the central areas with a better environmental quality and adequate infrastructure (Gusson *et al.*, 2012).

For decades, downtown has suffered a continuous degradation process and has gradually been abandoned by its residents. The city's plan distribution is very uneven, with massive urban sprawl in its peripheries and decades-long population decrease in its central areas. Latest census data (IBGE, 2010) point out that there was a general population increase in all districts, including the central ones, maintaining the different proportion of the population among central and peripheral districts. This population increase in central

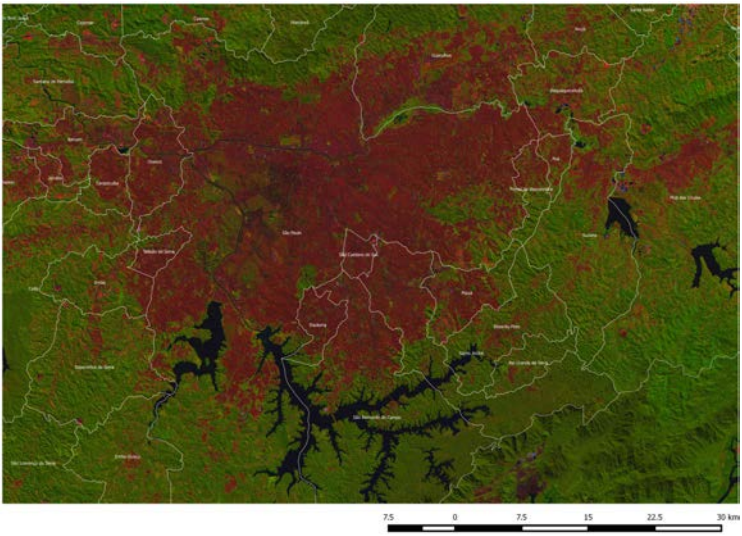


Figure 5.3. Part of São Paulo metropolitan region, encompassing 39 municipalities, showing the urbanized area with the more preserved green in the outskirts and water reservoirs in the south. Inside the urbanized area, significant spots of green are more evident in the west zone of the city, contrasting with the arid central and east zone. (Source: color composition from spectral bands 5, 4 and 3, from Landsat-5, May 23, 2011. CESAD-FAU/USP)

Figure 5.4. São Paulo seen from above; on the left the high-rise mixed-use downtown, with some small green oases, looking towards Bela Vista neighborhood; on the right, a low-rise industrial area, currently housing commerce and services as well, in Bras, one of the central neighborhoods, without any green. (Aerial pictures: L. Ferreira, 2010)

Figure 5.5. São Paulo seen from above; on the left, contrasts between the formal and informal city, including green infrastructure, in Vila Andrade district, and on the right, the arid low-rise periphery, in Cidade Ademar, southern São Paulo, almost devoid of vegetation. (Aerial pictures: L. Ferreira, 2010)

neighborhoods seems to be motivated by better urban infrastructure, especially public transportation, and proximity to jobs, considering hours lost in commuting in everyday life.

Regarding green infrastructure, the environmental services that the urban forest provides, such as urban warming mitigation, water management, soil stability and biodiversity, have been disregarded in the city and the distribution of green is definitely non-uniform. The spatial distribution and environmental quality of parks reflects the inequalities found in social and economic aspects. The wealthiest neighborhoods are characterized by large amount of vegetation and street trees, while some downtown areas and especially the east zone of the city are almost devoid of vegetation. Many districts, even in the formal city, are deprived of green infrastructure. Although the city administration states that the average green area per inhabitant in the city is 12.5 m^2, many sub-regions have almost zero (Fig. 5.6). The average green area per sub-region is 9.28%, with large inequalities[7] (Fig. 5.7).

A recent study from Ferreira (2015) showed that despite the lack of systematic data about the evolution of green areas in São Paulo, it can be deduced that a decrease in the urban forest has occurred

[7]Available at https://www.nossasaopaulo.org.br/observatorio/index.php (accessed 3 May 2015).

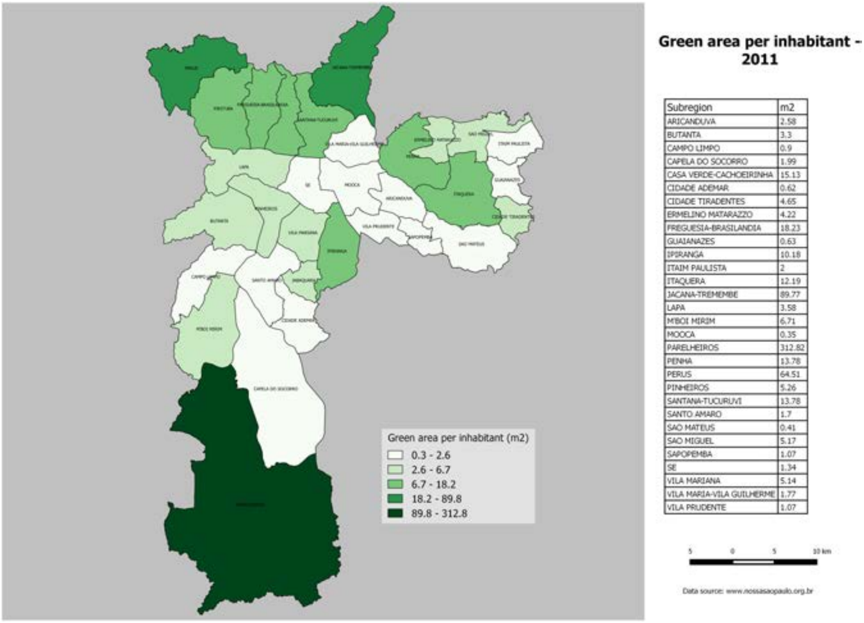


Figure 5.6. Percentage of green area per inhabitant in the city of São Paulo — 2011. (Data source: www.nossasaopaulo.org.br (Source: CESAD-FAU/USP and L. Ferreira))

over the past decades. Since 1971, both legal and illegal occupation have removed 31% of the existing natural vegetation, destroyed hills, filled floodplains with slums and avenues, and moved onto the banks of water reservoirs (located mainly in the south of the city), depleting the water quality. The study analyzed the approval process for vegetation clearance and the environmental compensation methods in force in São Paulo and showed that the costs and benefits of urban forest are not considered in their broader aspects. Due to the fact that São Paulo's Environmental Agency allows the conversion of trees to be planted in services or works as a compensation method to offset tree loss, the urgency to establish better parameters for this conversion process is clear. Considering worldwide efforts to find methods to value environmental goods and services, it is not sufficient to consider that the value of a tree is primarily the cost of planting. Increasing restrictions on tree removal and increasing the value of environmental

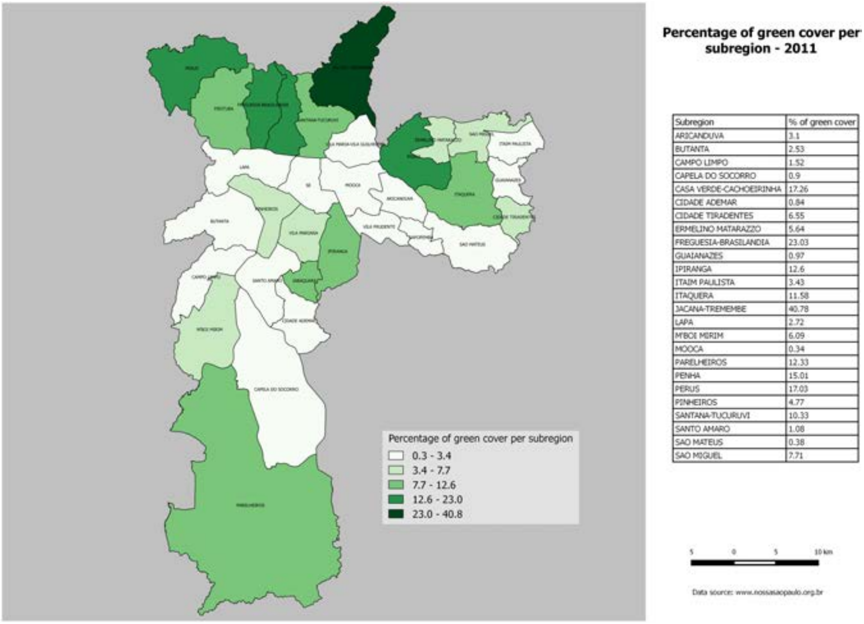


Figure 5.7. Percentage of green cover per sub-region — 2011. (Data source: www.nossasaopaulo.org.br (Source: CESAD-FAU/USP and L. Ferreira)).

compensation, decoupled from other measures, do not guarantee the preservation of vegetation, especially in target areas for the high-income real estate market. Comparing vegetation loss detected from satellite images with the number of requests for legal cuttings submitted to the local environmental agency, it is possible to verify no spatial correspondence between the two. No real-time monitoring with satellite images has been performed in the fourth biggest city in the world, but satellite images are successfully applied in monitoring Amazon deforestation in Brazil.

In São Paulo, there is a spatial coincidence between the urban expansion areas and the environmentally fragile areas (with the best preserved forest fragments and the water reservoirs). The lack of governmental control over the city's territory, especially on the outskirts of the city, put these areas in permanent risk. For all those reasons, it is urgent to develop new programs and preservation measures that encourage the maintenance and increase of tree cover. Among other limitations is the fact that there may be not enough physical space to replant trees once construction works have finished. This suggests the need for an alternative plan to guide tree removals, environmental compensation and re-planting, based on the benefits and environmental costs of urban vegetation (Ferreira, 2015), what is currently an ongoing study in this group.

5.4.1 *Local green and microclimate measurements (co-written with Paula Shinzato)*

Measurements in downtown urban parks have been carried out by the Laboratory of Environment and Energy Studies (LABAUT — FAUUSP), in Água Branca (Duarte and Gonçalves, 2006) and Luz Park (Spangenberg *et al.*, 2008; Shinzato and Duarte, 2011). More recently, two better equipped field campaigns were carried out at Trianon Park (Tenente Siqueira Campos Park), situated on Paulista Avenue, one of the main avenues in the city (Shinzato *et al.*, 2013a, 2013b; Shinzato, 2014).

Two non-destructive indirect methods were applied between August and September 2012 to estimate the average leaf density for trees canopy: plant canopy analyzer (using LAI-2000 (Li-Cor)) and hemispherical photographs (wide-angle 8 mm lens and a digital camera (Nikon COOLPIX 4500 plus FC-E8) used under an overcast sky). Digital images were post-processed in Can-eye Software[8] after calibration of the camera and the lens following recommended procedures (Shinzato *et al.*, 2013a; 2013b). Prior to the field campaign, a 20×20 m grid was established over the site plan of Trianon Park to define 22 points for on-site tree canopy measurements (Fig. 5.8).

Comparison of the two effective LAI measurement methods show the average LAI values varied between 2.14 (hemispheric photographs) and 2.52 (plant canopy analyzer). Each system has its specific measuring procedures and the method selection has to consider the local conditions (Fig. 5.9). This park has a dense arrangement of trees with few open spots and, in this case, the technique using

[8]Developed by INRA (National Institute of Agronomical Research) (2003). Available at http://www6.paca.inra.fr/can-eye, accessed February 2014.

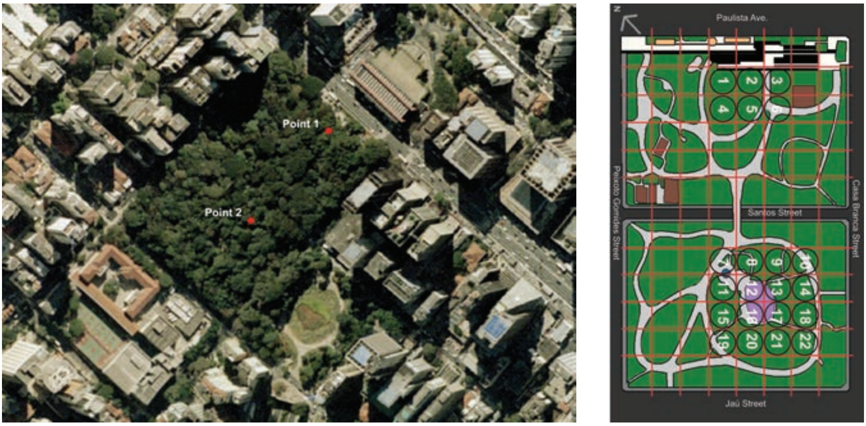


Figure 5.8. On the left, Trianon Park with the two microclimate measurements points in which meterorological stations were located and on the right, the 22 LAI measurements' grid over the site, at Paulista Avenue. (Source: digital ortophoto 1:5000 — Emplasa 2007. Available at http://www.cesadweb.fau.usp.br, accessed 18 June 2014. Drawings by P. Shinzato)

Figure 5.9. LAI measurements with the plant canopy analyzer and the hemispherical pictures technique at Trianon Park, 2012. (Photos: P. Shinzato)

hemispherical images had a better application when compared to the plant canopy analyzer. The hemispherical images are also visual data, registering the tree canopy, density and distribution of leaves, which may be of interest for comparative seasonal studies to evaluate different species, etc.

Microclimatic data were collected using two Campbell Scientific weather stations during four consecutive days in two different periods: 28 September–1 October 2012 (with an unusual occurrence of cold days at this time of the year); and 13–16 November 2013 (warm days). Each station included a shielded air temperature and relative humidity sensor, pyranometer for global solar radiation, soil temperature probe, black globe with a temperature probe inside, and 2Ds sonic anemometer for wind direction and speed (Fig. 5.10). Additionally, surface temperature was registered using a FLIR i40 hand-held infrared camera. All results are shown in LST (local standard time) for November 2013.

Results (Fig. 5.11) show that, despite the close results between the two stations, air temperature at point 2 was slightly lower due to a denser tree canopy cover (in November 2013, effective LAI $\sim$ 3 and natural soil conditions compared to effective LAI $\sim$ 1.5 and next to a pervious paved pedestrian path at point 1). Nevertheless, temperature differences inside Trianon Park reached 1.9°C on 15

Figure 5.10. Meteorological stations at points 1 and 2 inside Trianon Park, set up at 1.5 m above ground level, in November 2013. (Photos: P. Shinzato)

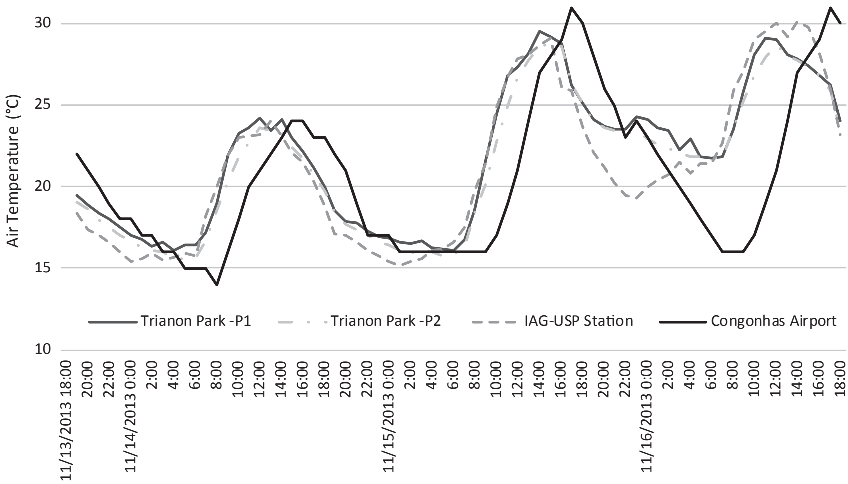


Figure 5.11. Air temperature (°C) registered inside Trianon Park (points 1 and 2), Congonhas Airport (WMO 83780) and IAG/USP — Água Funda (WMO 83004).

November, at 1300 h. The highest air temperature (31.5°C) occurred in Congonhas Airport at 1500 h. Another reference station (IAG-USP Água Funda station), located inside a park much wider than Trianon but with the station itself over grass without any shade, shows a larger long-wave radiation loss during nighttime in relation to Trianon Park.

Compared to the park environments, Congonhas Airport reference station is in general warmer during the day and cooler at night due to the open sky site and impervious surroundings without shade, which allows a higher long-wave radiation loss during nighttime. On the other hand, the park environments, especially Trianon, with the two meteorological stations placed under a dense tree cover, is slightly warmer at night, as expected even for a semi-confined green space.

The specific humidity comparison (Fig. 5.12) shows the actual moisture content, contrasting the drier airport environment with the more humid park sites, mainly due to grass, natural soil and a dense tree canopy. Humidity conditions at both points 1 and 2 inside Trianon Park were in between IAG/USP Água Funda and Congonhas Airport.

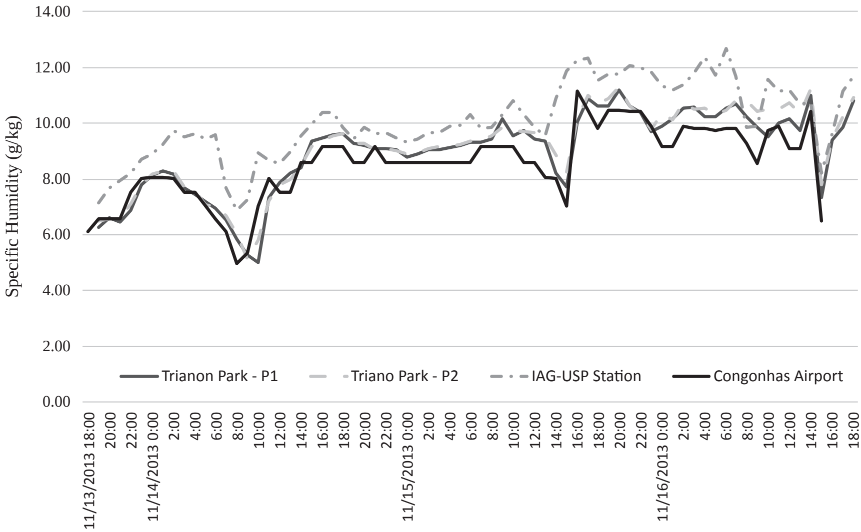


Figure 5.12. Calculated specific humidity (g/kg) based on registered data inside Trianon Park (points 1 and 2), Congonhas Airport (WMO 83780) and IAG/USP — Água Funda (WMO 83004).

Field measurements of microclimate, soil and vegetation data were then used to calibrate ENVI-met 3.1 to the local sub-tropical climate conditions. After that, parametric studies were carried out to test the sensitivity of the model to tree canopy typology, wind speed, soil humidity and the extension of microclimate effects beyond the park (Shinzato, 2014).

Simulation results under a dense canopy (elliptical canopy form, LAI = 5) showed an average reduction of 1°C in air temperature and 19°C in surface temperature at the ground, compared to the outside conditions. The higher evapotranspiration and the significantly lower surface temperature under the tree canopy led to a dramatic drop in mean radiant temperature. This is the parameter most affected by shading trees and buildings. The reduction in mean radiant temperature through shading results from both less received direct, diffuse and reflected short-wave radiation from the sun and lower surface temperatures and thereby lower thermal (long-wave) radiation from urban surfaces, affecting positively the thermal comfort indices for tropical and sub-tropical climates. Both PET (Höppe, 1999) and TEP (Monteiro and Alucci, 2011) developed for local conditions are significantly influenced by the mean radiant temperature. The park can represent a reduction from 3°C (point 1) to 5°C (point 2) in the adaptive thermal index TEP compared to the nearby outside.

Beyond the park limits, the maximum extension of these effects at street level were up to 5 m towards downwind direction at wind speed of 1 m/s and 40% for soil humidity in the upper layer (0–20 cm).

5.5 Concluding Remarks

The cooling effect of vegetation depends on urban configuration, soil temperature and humidity, LAI, green area distribution and overall climate conditions; air temperature is not the most important cooling parameter. Seemingly small differences in air temperature, together with significant reductions in mean radiant temperature and evapotranspiration could lead to a 3–5°C drop in thermal sensation, and could be even more depending on the contrasts between the park and the surrounding environment, e.g. during the dry season and with some kind of irrigation.

However, the street level green microclimate effect is very local under low wind speed, extending only to a few meters outside the green areas. As pointed out by other previous studies, this suggests that it is better to have more small spots of green distributed and linked in the city than concentrated in a few bigger plots.

None of these scenarios will reverse long-term warming trends, but combinations of these strategies can moderate the extreme climate events, such as those that occurred during summer 2014 and 2015, allowing resting places in open and semi-confined spaces in which people can recover themselves from extreme conditions.

At first sight, buildings and green appear to compete for space in urban areas but sometimes there are no green at all, even in low-density areas. This suggests that there is scope for greenery in urban areas. Assuming that densification is inevitable and desirable from the point of view of urban sustainability, discussion and design proposals (such as Fig. 5.13) must include green infrastructure to counterbalance increasing built density in different city scales, urban and climatic contexts, including climate change scenarios which are already taking shape in many cities in the world.

A greener city and the mitigation of urban warming effects, among other environmental services, is possible only through the implementation of city-wide changes, from groups of trees to large-scale green interventions, encouraged by building codes and citizen's initiatives. Recently, neighborhood organizations in São Paulo have begun to challenge the municipal administration and are planting trees without permission, after a negative answer from the City Hall (for example, Largo da Batata (Fig. 5.14), almost a desert from the microclimate point of view, housing a public transport terminal in Pinheiros' district).

Informal or temporary expressions of green infrastructure are being raised in the city of São Paulo, even in very small-scale interventions, like the parklets in some neighborhoods, or in a few spots of green inside the informal city, as pointed out in the beginning of this chapter.

Since April 2014, the municipal administration in São Paulo has regulated the installation and use of parklets,[9] a temporary extension of sidewalks, and has the first Latin American public policy on the issue. A parklet is defined as the settlement of a platform over the street, usually occupying a place destined for on-street parking, equipped with benches, flowerbeds, tables and chairs, shadow umbrellas, gym facilities, bicycle parking facilities and similar urban furniture, to support resting or leisure activities in the city (Fig. 5.15). All the facilities must be entirely open to the public, 24 hours a day, whether or not the sponsors are public or private.

The new masterplan for São Paulo,[10] in force since 31 July 2014, set up guidelines for the city's development and growth for the next 16 years. One of the goals is to bring housing and jobs closer, facing the social and territorial inequalities. In order to achieve these goals,

[9] Available at http://gestaourbana.prefeitura.sp.gov.br/parklets/, accessed 4 May 2015.
[10] Available at http://gestaourbana.prefeitura.sp.gov.br/principal-pde/, accessed 4 May 2015.

Figure 5.13. Design proposal for greening the most popular commercial street in São Paulo, Rua 25 de Março, downtown, a dense and arid area in the city. (Source: B. Mendes, Diploma Project, FAUUSP, 2007)

Figure 5.14. Largo da Batata, almost a desert from the microclimate point of view, housing a public transport terminal in Pinheiros' district. Users are planting trees and improvising shade. (Pictures: D. Duarte, 2015)

several strategies, among others, were defined: fighting vacant land, implementing affordable housing policies, improving urban mobility, guiding development growth near public transportation routes and nodes, strengthening public participation in the decisions about the future of the city and incorporating the environmental agenda. The plan and the forthcoming revisions of the land-use policy and building code, including the environmental quota[11] create an opportunity for government and citizens to propose new forms of green infrastructure incorporated into municipal regulations.

Green public policies are increasingly being established worldwide, such as the Green Plot Ratio in Singapore, BAF in Berlin and also used in other German cities, SGF in Seattle, WA, and the

[11]Available at http://gestaourbana.prefeitura.sp.gov.br/cota-ambiental-2/, accessed 4 May 2015.

Figure 5.15. Parkets in São Paulo, at Oscar Porto, Maria Antonia, Harmonia and Fidalga streets. (Photos: L. Ferreira, E. Pizarro, D. Duarte, 2015)

GSF used in parts of Malmö and Lund, Sweden. The São Paulo environmental quota, currently under discussion, intends to propose a new urban tool, to be applied during licencing process over private land, embedded in the land-use policy. The quota establishes drainage and green criteria, aiming to encompass biodiversity, microclimate and drainage issues. The aim of the tool is to have a mandatory minimum score to be fulfilled by the land owner. Topics for this agenda should also include green property tax (active in some Brazilian cities), governance issues, links between green infrastructure with population and built density (which is still missing in local discussions), vegetation clearance criteria, etc. These issues demand the availability of official public data, updated vegetation maps, permanent climate and green monitoring, inventory of actual amount of green related to its ecosystem services, etc. The development of such resources will enable better research and public policy discussion to bridge the deficit in green infrastructure in urban areas, one of the missing links in green design.

Acknowledgments

Funding was provided by the following organisations: Conselho Nacional de Desenvolvimento Científico e Tecnológico — CNPq, research funding and undergraduate scholarships; Fundação de Amparo à Pesquisa do Estado de São Paulo — FAPESP, graduate students' scholarships.

The author is grateful to Secretaria Municipal do Verde e do Meio Ambiente — SVMA, São Paulo, and to LABAUT staff, FAUUSP, for their assistance in the field measurements, especially to the 'green group' of research including Paula Shinzato, PhD, Erik Johansson, PhD, Jörg Spangenberg, PhD; former and current undergraduate students Lara del Bosco, Erika Osako, Natália Turri Lorenzo, Fernanda Camargo Barros, Barbara Ferronato, Denise Cordeiro Moreira and to our technician Ranieri Carvalho Higa.

The following assistance is gratefully acknowledged:

- Prof Michael Bruse and his laboratory's team from the Environmental Modelling Group (Geoinformatik/EMG), Geographisches

Institut Johannes Gutenberg, Universität Mainz, for assistance with ENVI-met;

- Prof Nyuk Hien Wong, National University of Singapore, for STEVE software licence;
- Prof Dr Demóstenes Ferreira da Silva Filho (ESALQ/USP), for the loan of equipment and all the collaboration with our research group;
- Prof Dr Humberto Ribeiro da Rocha (IAG/USP) for humidity soil data and all the collaboration with our research group.
- Institute of Astronomy, Geophysics and Atmospheric Sciences, University of São Paulo IAG/USP, for providing climatic data.

References

Akbari, H. *et al.* (2001). Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas, *Solar Energy*, **70**(3), 295–310.

Ali-Toudert, F. and Mayer, H. (2007). Effects of asymmetry, galleries, overhanging façades and vegetation on thermal comfort in urban street canyons, *Solar Energy, Tampa*, **81**, 742–754.

Aragão, L.E., Shimabukuro, Y.E., Santo, F.D.B. *et al.* (2005). Landscape patterns and spatial variability of leaf area index in eastern Amazonia, *Forest Ecology and Management*, **211**, 240–253.

Barclay, H.J., Trofymow, J.A. and Leach, R.I. (2000). Assessing bias from boles in calculating leaf area index in immature Douglas-fir with the LI-COR canopy analyzer, *Agricultural and Forest Meteorology*, **100**, 255–260.

Bonan, G. (2010). *Ecological Climatology: Concepts and Applications. 2nd ed.*, Cambridge University Press, Cambridge, UK.

Bowler, D. *et al.* (2010). Urban greening to cool towns and cities: A systematic review of the empirical evidence, *Landscape and Urban Planning*, **97**, 147–155.

Bruse, M. and Fleer, H. (1998). Simulating surface–plant–air interactions inside urban environments with a three-dimensional numerical model, *Environmental Software and Modelling*, **13**, 373–384.

Chatzidimitriou, A., Chrissomallidou, N. and Yannas, S. (2005). Microclimate modifications of an urban street in northern Greece, proceedings of PLEA 2005 — Passive and Low Energy Architecture, 13–16 November 2005, Beirut, Lebanon, 689–694.

Chen, J.M. and Black, T.A. (1992). Foliage area and architecture of clumped plant canopies from sunfleck size distributions, *Agricultural and Forest Meteorology*, **60**, 249–266.

Chen, M.J., Govind, A., Sonnentag, O. *et al.* (2006). Leaf area index measurements at Fluxnet-Canada forest sites, *Agricultural and Forest Meteorology*, **140**, 257–268.

Chen, Y. and Wong, N.H. (2006). Thermal benefits of city parks, *Energy and Buildings*, **38**, 105–120.

Davies, M. *et al.* (2008). Strategies for the modification of the urban climate and the consequent impact on building energy use, *Energy Policy*, **36**, 4548–4551.

Davis, M. (2007). *Planeta Favela*, Boitempo, São Paulo, Brazil.

de Munck *et al.* (2013). The GREENROOF module (v7.3) for modelling green roof hydrological and energetic performances within TEB 2013, *Geoscientific Model Development*, **6**, 1941–1960.

Demarez, V., Duthoit, S., Beret, F. *et al.* (2008). Estimation of leaf area and clumping indexes of crops with hemispherical photographs, *Agricultural and Forest Meteorology*, **148**, 644–655.

Duarte, D. and Serra, G.G. (2003). Padrões de ocupação do solo e microclimas urbanos na região de clima tropical continental brasileira. Correlações e proposta de um indicador, *Ambiente Construído, Porto Alegre*, **3**(2), 7–20.

Duarte, D. (2010). Variáveis urbanísticas e microclimas urbanos — modelo empírico e proposta de um indicador. Fórum Patrimônio: Ambiente Construído e Patrimônio Sustentável (UFMG. Online), *Clima Urbano e Planejamento das Cidades*, **4**(2). Available at http://www.forumpatrimonio.com.br/ (accessed August 2011).

Duarte, Denise; Gonçalves, Joana Carla Soares. Environment and Urbanization: Microclimatic Variations in a Brownfield Site in Sao Paulo, Brazil. In: 23rd International Conference PLEA 2006 — Passive and Low Energy Architecture, 2006, Geneve. Clever Design, Affordable Comfort. A Challenge for Low Energy Architecture and Urban Planning. Fribourg: Université de Genève, 2, 497–503.

Duarte, D. (2010). Variáveis urbanísticas e microclimas urbanos — modelo empírico e proposta de um indicador. Fórum Patrimônio : Ambiente Construïdo e Patrimǫnio Sustentável (UFMG. Online), **3**(2), 1–36.

Emmanuel, M.R. (2005). *An Urban Approach to Climate-Sensitive Design. Strategies for the Tropics*, Spon Press, New York, NY.

EnergyPlus Engineering Reference, 2014. The Reference to EnergyPlus Calculations. Available at: https://energyplus.net/sites/default/files/pdfs_v8.3.0/EngineeringReference.pdf

Erell, E., Pearlmutter, D. and Williamson, T. (2011). *Urban Microclimate: Designing the Spaces between Buildings*. Earthscan, London, UK.

FAO — Food and Agriculture Organization of the United Nations (2009. "Trees Connecting People: In Action Together", proceedings of the FAO collaborative meeting on urban & peri-urban forestry, 27–28 January 2009, Rome, Italy.

Ferreira, L.S. (2015). "Vegetation Management in São Paulo, Brazil: Clearing of Urban Vegetation and Environmental Compensation", in Johnston, M. and

Percival, G. (eds.), *Trees, People and the Built Environment II*, Institute of Chartered Foresters, Edinburgh, UK.

Giridharan, R. *et al.* (2008). Lowering the outdoor temperature in high-rise high-density residential developments of coastal Hong Kong: The vegetation influence, *Building and Environment*, **43**, 1583–1595.

Gonsamo, A. and Pellikka, P. (2009). The computation of foliage clumping index using hemispherical photography, *Agricultural and Forest Meteorology*, **149**, 1781–1787.

Gower, S.T., Kucharik, C.J., Norman, J.M. (1999). Direct and indirect estimation of leaf area index, f_{APAR}, and net primary production of terrestrial ecosystems, *Remote Sensing of Environment*, **70**, 29–51.

Grimmond, S. *et al.* (2011). Initial results from Phase 2 of the international urban energy balance model comparison, *International Journal of Climatology*, **31**, 244–272.

Grimmond, S. *et al.* (2010). The international urban energy balance models comparison project: first results from phase 1, *Journal of Applied Meteorology and Climatology*, **49**, 1268–1292.

Gusson, C.S., Madeira, A.H.Y. and Duarte, D. (2012). "São Paulo: A Dense City", proceedings of the 4th CIB International Conference on Smart and Sustainable Built Environments — SASBE2012: Emerging Economies, 28–30 June 2012, São Paulo, Brazil, 293–299 (e-book).

Höppe, P. (1999). The physiological equivalent temperature — a universal index for the biometeorological assessment of the thermal environment, *International Journal of Biometeorology*, **43**, 71–75.

Huttner, S. (2012). Further development and application of the 3D microclimate simulation ENVI-met, PhD Thesis, Mainz University, Germany.

IAG/USP. (2014). *Boletim Climatológico Anual da Estação Meteorológica do IAG/USP/ Seção Técnica de Serviços Meteorológicos*, Instituto de Astronomia, Geofísica e Ciências Atmosféricas da Universidade de São Paulo, Brazil.

IBGE. (2010). Instituto Brasileiro de Geografia e Estatística. Censo 2010. Available at http://www.censo2010.ibge.gov.br (accessed 2 August 2011).

Jauregui, E. (1990/91). Influence of a large urban park on temperature and convective precipitation in a tropical city, *Energy and Buildings*, **15–16**, 457–463.

Johansson, E. *et al.* (2013). Scale-integrated atmospheric simulations to assess thermal comfort in different urban tissues in the warm humid summer of São Paulo, Brazil, *Urban Climate*, **6**, 24–43.

Jonckheere, I., Nackerts, K., Muys, B. *et al.* (2005). Assessment of automatic gap fraction estimation of forests from digital hemispherical photography, *Agricultural Forest Meteorology*, **132**, 96–114.

Jonckheere, I. *et al.* (2004). Review of methods for in situ leaf area index determination Part I. Theories, sensors and hemispherical photography, *Agricultural and Forest Meteorology*, **121**, 19–35.

Jones, H.G. (2014). *Plants and Microclimate: A quantitative approach to environmental plant physiology. 3rd ed.*, Cambridge University Press, Cambridge, UK.

Jusuf, S.K. and Wong, N.H. (2009). "Development of empirical models for an estate level air temperature prediction in Singapore", proceedings of Second International Conference on Countermeasures to Urban Heat Island, 21–21 September 2009, Berkeley, CA. Available at http://heatisland2009.lbl.gov/docs/221410-jusuf-doc.pdf (accessed 19 June 2014).

Jusuf, S.K., Wong, N.H. and Tan, E. (2014). "Urban Climatic Mapping: A Tool to Support Urban Planning and Design in Climate-responsive Cities", proceedings of the Third International Conference on Countermeasures to Urban Heat Island, 13–15 October 2014, Venice, Italy.

Kallarackal, J. and Somen, C.K. (1997). An ecophysiological evaluation of the suitability of *Eucalyptus grandis* for planting in the tropics, *Forest Ecology and Management*, **95**, 3–61.

Kumagai, T., Saitoh, T.M., Sato, Y. *et al.* (2004). Transpiration, canopy conductance and the decoupling coefficient of a lowland mixed dipterocarp forest in Sarawak, Borneo: Dry spell effects, *Journal of Hydrology*, **287**, 237–251.

Lee. S. and Park, S.A. (2008). Vegetated urban canopy model for meteorological and environmental modelling, *Boundary-Layer Meteorology*, **126**, 73–102.

Lemonsu, A. *et al.* (2012). Inclusion of vegetation in the town energy balance model for modelling urban green areas, *Geoscientific Model Development*, **5**, 1377–1393.

Masson, V. (2000). A physically-based scheme for the urban energy budget in atmospheric models, *Boundary-Layer Meteorology*, **94**, 357–397.

Monteiro, L. and Alucci, M. (2011). "Proposal of an outdoor index: empirical verification in the sub-tropical climate", proceedings of the 27th Conference on Passive and Low Energy Architecture PLEA, 13–15 July 2011, Louvain-la-neuve, Belgium.

Ng, E. *et al.* (2012). A study on the cooling effects of greening in a high-density city: an experience from Hong Kong, *Building and Environment*, **47**, 256–271.

Oke, T.R. (1987). *Boundary Layer Climates*, Routledge, London, UK.

Ong, B.L. (2015). "Green Plot Ratio and the Role of Greenery in Low Carbon Living Boon Lay Ong", in Lehmann, S., *Low Carbon Cities: Transforming Urban Systems*, Routledge, New York, NY, 349–360.

Ong, B.L. (2002). Green plot ratio: an ecological measure for architecture and urban planning, *Landscape and Urban Planning*, **63**, 197–211.

Ong, B.L., Ho, A. and Ho, K.H. (2012). "Green Plot Ratio — Past, Present and Future", in Tropics 2050 — iNTA 2012 — 4th International Network for Tropical Architecture, 12–14 December 2012, Singapore.

PBMC (Painel Brasileiro de Mudanças Climáticas) (2013a). *Contribuição do Grupo de Trabalho 1 ao Primeiro Relatório de Avaliação Nacional do Painel Brasileiro de Mudanças Climáticas*, Sumário Executivo GT1, Rio de Janeiro, Brazil.

PBMC (2013b). *Contribuição do Grupo de Trabalho 2 ao Primeiro Relatório de Avaliação Nacional do Painel Brasileiro de Mudanças Climáticas*, Sumário Executivo do GT2, Rio de Janeiro, Brazil.

PBMC (2013c). *Contribuição do Grupo de Trabalho 3 ao Primeiro Relatório de Avaliação Nacional do Painel Brasileiro de Mudanças Climáticas*, Sumário Executivo do GT3, Rio de Janeiro, Brazil.

Redon, E. *et al.* (2014). "Modelling of Urban Vegetation as a Thermal Regulator and Management of Associated Water Resources for Neighbourhood to City-scale Applications", proceedings of the Third International Conference on Countermeasures to Urban Heat Island, 13–15 October 2014, Venice, Italy, 850–852.

Sailor, D. (2008). A green roof model for building energy simulation programs, *Energy and Buildings*, **40**, 1466–1478.

São Paulo (City) (2010). *Secretaria Municipal de Habitação. Superintendência de Habitação Popular. A Cidade Informal no Século XXI*, Sehab, São Paulo, Brazil. Available at http://www.habisp.inf.br/theke/documentos/publicacoes/catalogo_exposicao/index.html (accessed 26 May 2015).

Shashua-Bar, L. and Hoffman, M.E. (2004). Quantitative evaluation of passive cooling of the UCL microclimate in hot regions in summer, case study: urban streets and courtyards with trees, *Building and Environment*, **39**, 1087–1099.

Shashua-Bar, L. and Hoffman, M.E. (2002). The Green CTTC model for predicting the air temperature in small urban wooded sites, *Building and Environment*, **37**, 1279–1288.

Shashua-Bar, L. and Hoffman, M.E. (2000). Vegetation as a climatic component in the design of an urban street an empirical model for predicting the cooling effect of urban green areas with trees, *Energy and Buildings*, **31**, 221–235.

Shinzato, P. (2014). Impacto da vegetação nos microclimas urbanos em função das interações solo-vegetação-atmosfera, PhD Thesis, FAU-USP. Available at http://www.teses.usp.br/teses/disponiveis/16/16132/tde-12092014-115829/pt-br.php (accessed 19 June 2014).

Shinzato, P. and Duarte, D. (2011). Impact of Vegetation on Urban Microclimates. In: *World Sustainable Building Conference 2011*, Helsinki. World Sustainable Building Conference. Helsinski: SB11, **2**, 239–247.

Shinzato, P., Duarte, D.H.S., Barros, F.C. *et al.* (2013). "Intensity and Spatial Influence of Urban Parks: a case study in São Paulo", in proceedings of the Sustainable Building Conference, 25–28 September 2013, Graz, Austria.

Shinzato, P. and Duarte, D. (2012). "Microclimatic Effect of Vegetation for Different Leaf Area Index — LAI", proceedings of PLEA 2012 — Passive and Low Energy Architecture , 7–9 November 2012, Lima, Peru, 1–6.

Shinzato, P., Duarte, D., Barros, F. *et al.* (2013a). "Intensity and Spatial Influence of Urban Parks: a case study in São Paulo, Brazil", in proceedings of the Sustainable Building Conference, 25–28 September 2013, Graz, Austria.

Shinzato, P., Duarte, D., Barros, F., *et al.* (2013b). "O impacto da vegetação nos microclimas urbanos: estimativa do índice de área foliar em diferentes grupos arbóreos", XII Encontro Nacional de Conforto no Ambiente Construído/VIII Encontro Latinoamericano de Conforto no Ambiente Construído, 25–27 September 2013, Brasília, Brazil.

Spangenberg, J. (2004). Improvement of Urban Climate in Tropical Metropolis — A case study in Maracanã/Rio de Janeiro, Master's Thesis, University of Applied Sciences, Cologne, Germany. Available at http://www.basis-id.de/science (accessed 3 March 2008).

Spangenberg, J. *et al.* (2008). Simulation of the influence of vegetation on microclimate and thermal comfort in the city of São Paulo. *Revista da Sociedade Brasileira de Arborização Urbana*, **3**, 1–19.

Spangenberg, J., Shinzato, P., Johansson, E. *et al.* (2007). Simulation of the influence of vegetation on microclimate and thermal comfort in the city of São Paulo, *RevSBAU, Piracicaba*, **3**(2), 1–19.

Spronken-Smith, R.A. and Oke, T. (1998). The thermal regime of urban parks in two cities with different summer climates, *International Journal of Remote Sensing*, **19**(11), 2085–2104.

Stone Jr., B. (2012). *The City and the Coming Climate. Climate Changes in the Places we Live*, Cambridge, New York, NY.

Swaid, H. and Hoffman M.E. (1990). Prediction of urban air temperature variations using the analytical CTTC model, *Energy and Buildings*, **14**, 313–324.

Trichon, V., Walter, J.M.N. and Laumonier, Y. (1998). Identifying spatial patterns in the tropical rain forest structure using hemispherical photograghs, *Plant Ecology*, **137**, 227–247.

UN DESA (United Nations — Department of Economic and Social Affairs) (2014). *World Urbanization Prospects: The 2014 Revision*, Highlights.

Vertessy, R.A., Benyon, R.G., O'Sullivan, S.K. *et al.* (1995). Relationships between stem diameter, sapwood area, leaf area and transpiration in a young mountain ash forest, *Tree Physiology*, **15**, 559–567.

Watson, D.J. (1947). Comparative physiological studies on growth of field crops: I. Variation in net assimilation rate and leaf area between species and varieties, and within and between years, *Annals of Botany*, **11**, 41–76.

Weiss, M., Baret, F., Smith, G.J. *et al.* (2004). Review of methods for *in situ* leaf area index (LAI) determination. Part II. Estimation of LAI, errors and sampling, *Agricultural and Forest Meteorology*, **121**, 37–53.

Weiss, M. and Baret, F. (2010). CAN-EYE V6.1 User Manual, EMMAH laboratory (Mediterranena environment and agro-hydro system modelisation), French National Institute of Agricultural Research (INRA).

Wong, N.H. and Chen, Y. (2009). *Tropical Urban Heat Islands: Climate, buildings and greenery*, Taylor and Francis, Abingdon, UK.

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

Wong, N.H. *et al.* (2003). The effects of rooftop garden on energy consumption of a commercial building in Singapore, *Energy and Buildings*, **35**, 353–364.

Wong, N.H., Jusuf, S.K. and Tan, C.L. (2011). Integrated urban microclimate assessment method as a sustainable urban development and urban design tool, *Landscape and Urban Planning*, **100**, 386–389.

Wong, N.H. and Jusuf, S.K. (2008a). An assessment method for existing greenery conditions in a university campus, *Architectural Science Review*, **51**(3), 212–222.

Wong, N.H. and Jusuf, S.K. (2008b). GIS-based greenery evaluation on campus master plan, *Landscape and Urban Planning*, **84**(2), 166–182.

Xavier, A.C., Soares, J.V. and Almeida, A.C. (2002). Variação do Índice de Área Foliar em Clones de Eucalipto ao longo do seu ciclo de crescimento, *Árvore*, **26**(4), 421–427.

Yang, W. *et al.* (2013). Thermal comfort in outdoor urban spaces in Singapore, *Building and Environment*, **59**, 426–435.

Yok, T.P. and Sia, A. (2010). *Leaf Area Index of Tropical Plants — A Guidebook on its Use in the Calculation of Green Plot Ratio*, CUGE, Singapore.

Zhang, Y., Chen, J.M. and Miller, J.R. (2005). Determining digital hemispherical photograph exposure for leaf area index estimation, *Agricultural and Forest Meteorology*, **133**, 166–181.

Chapter 6

Urban thermal comfort in the tropics

Erik Johansson

6.1 Introduction

Cities are getting increasingly hotter, which has adverse effects on the health and well-being of urban dwellers. The problem is especially serious in tropical climates. Subjective outdoor thermal comfort has received increased attention in the latest decade and the number of studies has increased each year (Johansson *et al.*, 2014). Compared to indoors, the outdoor thermal environment is complex and there are large temporal and spatial variations; thermal conditions span from thermal comfort to a stressful environment. Many studies have found that outdoors the thermal comfort range is wider than indoors (Spagnolo and de Dear, 2003, Lin, 2009; Lin *et al.*, 2011, Yahia and Johansson, 2013). Thermal adaptation — which can include physiological, psychological and behavioral factors — has proven to play an important role in subjective thermal comfort assessment (Lin, 2009; Nikolopoulou and Steemers, 2003; Knez and Thorsson, 2006).

This chapter seeks to discuss and clarify issues related to thermal comfort in the tropics. How the thermal environment affects the human body is discussed in Sec. 6.2 with emphasis on warm-humid conditions. The variables that influence thermal comfort and heat stress in tropical climates are dealt with in Sec. 6.3. A great number of comfort and heat-stress indices predicting the thermal environment exist, and in Sec. 6.4 some common indices are described and their appropriateness in the tropics evaluated. A common approach to investigating the subjective thermal comfort is through field surveys using measurements and questionnaires; the design of such studies is discussed in Sec. 6.5. Finally, Sec. 6.6 deals with the assessment of thermal comfort, thermal neutrality and thermal preference based on measurements and questionnaires.

6.2 Effect of the Thermal Environment on the Human Body

The human body produces heat as a result of metabolic activities (digestion of food and physical activity). This heat must be continuously released in order to avoid the overheating of the body — so-called *hyperthermia*. On the other hand, if the heat losses are larger than the heat produced then the body cools down, which is called *hypothermia*. At sedentary activity in comfortable environments the body core temperature is about 37°C and the skin temperature is about 33–34°C (McIntyre, 1980). If the body activity increases (increased metabolic rate) the body's internal temperature will rise whereas the skin temperature is hardly affected (McIntyre, 1980). For health reasons it is important to maintain the internal body temperature as constant as possible.

The heat produced by a person at rest is about 58 W/m^2 skin surface (ASHRAE, 2001). Applying the standard skin surface area of 1.8 m^2, this corresponds to about 100 W.[1]

6.2.1 *The energy balance of the human body*

A common way to describe the thermal state of the human body is to study its energy balance. Several thermal indices that predict thermal comfort and stress (see Sec. 6.4), are based on the energy balance of the human body. The principle of the energy balance is that the heat produced by the body must be compensated for by heat loss. The heat loss occurs via the skin and respiration. The energy

[1] In reality women have lower skin surface area than men and the skin surface may vary largely between people from different geographical regions and ethnic groups (ASHRAE, 2001). For the thermal index PT (Sec. 7.4.1.1), a body surface area of 1.9 m^2 is assumed (Staiger *et al.*, 2012).

balance of the human body can be expressed as (ASHRAE 2001; Emmanuel 2005a; Höppe 1999):

$$H = M - W = (C_s + R_s + E_s) + (C_r + E_r) + S, \tag{6.1}$$

where

$H =$ net heat production of the body,
$M =$ metabolic heat production,
$W =$ external work,
$C_s =$ convective heat loss (gain) from (to) the skin,
$R_s =$ radiative heat loss (gain) from (to) the skin,
$E_s =$ evaporative heat loss from the skin,
$C_r =$ convective heat loss from respiration,
$E_r =$ evaporative heat loss from respiration,
$S =$ heat storage in skin and body core.

All units in Eq. (6.1) are in watts (W) or $\mathrm{W/m^2}$ body area. The rate of heat production, M, depends on the physical activity. M is always positive and typically varies between $40\,\mathrm{W/m^2}$ while sleeping and around $225\,\mathrm{W/m^2}$ when performing heavy manual work (McIntyre 1980; ASHRAE 2001). For a standard person of $1.8\,\mathrm{m^2}$ this corresponds to about 70 W and 400 W, respectively. In some activities external work is done by the muscles, e.g. when climbing uphill or performing manual work. The energy needed for such activities, the rate of external work W, is taken from the metabolic energy. As a result the *net heat production*, H, of the body is reduced, i.e. $H = M - W$. The external work, W, is zero for low levels of activity such as lying, sitting, standing and walking. However, at higher levels of activity, e.g. when carrying out physical work or sports, W can reach levels between 10% and 20% of M (McIntyre, 1980).

Sensible heat loss from the skin through convection (C_s) and radiation (R_s) will occur if the body's skin temperature is higher than the ambient air temperature and mean radiant temperature (T_{mrt}, see Sec. 6.3) respectively. If, on the other hand, the air temperature and the T_{mrt} are higher than the skin temperature, then the body will gain heat. Latent heat loss from the skin (E_s) occurs through evaporation of sweat and skin moisture. Heat is also dissipated from the lungs during respiration as both sensible (C_r) and latent (E_r) heat.

If the body's internal net heat production (H) is higher than the heat losses this will lead to storage (S) of heat and subsequent rise of the body's temperature. Conversely, heat production lower than the heat losses will result in storage of cold.

6.2.2 *Response of the human body to high temperatures*

At high temperatures the body responds in different ways. Heat is removed from the core of the body to the skin where cooling is more effective. When the internal body temperature rises above a certain 'setpoint' level, more blood is transported towards the skin through vasodilation (widening) of blood vessels. At extremely hot conditions the increase in skin blood flow may be 15 times (ASHRAE, 2001).

Heat is also lost through sweating (E_s in Eq. (6.1)). When the internal body temperature increases, the sweating starts at the skin. Due to evaporative cooling this helps lower the skin temperature and also creates heat loss from the body core. If the air is dry, then the evaporation is effective and the skin remains dry even at high sweat rates (ASHRAE, 2001). If, however, the air is humid, then the evaporation is less effective and the sweat will spread out on the skin in order to be able to evaporate. This increases the so-called skin wettedness, which is the portion of the skin that is covered with water (Givoni, 1998; ASHRAE, 2001). At low activity skin wettedness above 25% is considered uncomfortable (ASHRAE, 2001).

When the air is dry the human body can resist high temperatures, at least for a limited period of time. However, when the air is humid the tolerance to heat decreases significantly because the evaporative cooling effect from the skin is restricted.

After long-term exposure to hot conditions the body core temperature at which sweating starts is increased. However, due to salt accumulation at the body surface the evaporation gets less effective and the skin wettedness increases. A way of the human body to adapt to high temperatures is through increased blood flow as well as through increased sweating in peripheral regions of the body where the heat transfer is more efficient. (ASHRAE, 2001)

6.2.3 *Health problems caused by heat stress*

Long exposure to high air temperatures may lead to heat stress and various kinds of heat illness. The heat stress results in higher deep body temperatures, which in turn leads to increased vasodilation and sweating, which in the end may lead to heat illnesses such as fainting (heat syncope), and, at high levels of activity, heat cramps, i.e. muscle pains. Another problem is heat exhaustion which may occur due to heavy exercise or work in a hot environment when sweating cannot dissipate the heat generated within the body. The phenomenon is characterized by profuse sweating, weakness, nausea, vomiting, headaches, muscle spasms and low fever. If the water lost by sweating is not replaced, dehydration may occur. Heat stroke, which is a life-threatening condition, occurs when the body fails to cool down and the body temperature increases above 41°C. Then sweating stops and a person may enter stages of confusion, seizure or coma. (ASHRAE, 2001; McIntyre, 1980)

6.3 Factors Influencing Thermal Comfort in Tropical Climates

Thermal comfort is defined as “that condition of mind which expresses satisfaction with the thermal environment” (ISO 7730, 2005). Thermal comfort is subjective and can therefore never be achieved by all people. In indoor environments that are space-conditioned, the number of people feeling comfortable is normally very high. Indoor standards such as ISO 7730 (2005) and ASHRAE 55 (ASHRAE, 2004) specify climate zones where 80% or 90% of the population, having a low level of activity, perceive the environment as thermally acceptable. In environments that are not space-conditioned — including outdoors — this is not possible to achieve, especially in difficult climates such as the warm-humid.

In tropical climates there is normally a distinct difference between dry and rainy seasons. Both temperature and humidity are higher during the rainy season, whereas wind speeds are often lower. The climate of Dar es Salaam, Tanzania is shown as an example in Fig. 6.1.

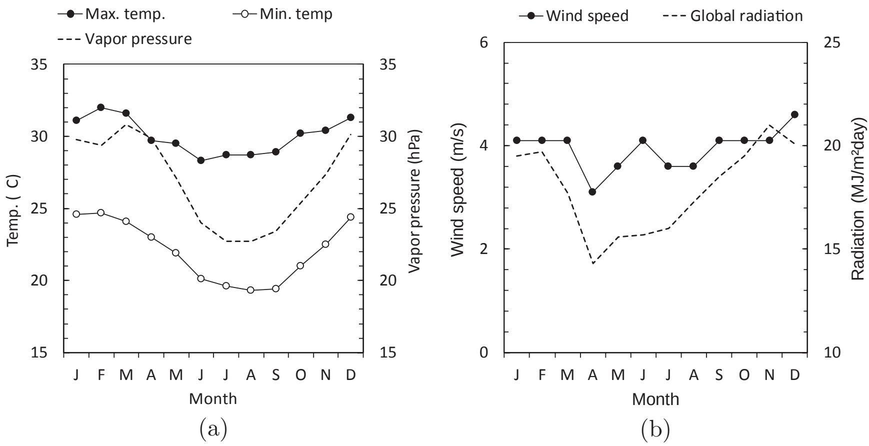


Figure 6.1. The climate of Dar es Salaam, Tanzania. (a) Mean maximum and minimum air temperature and vapor pressure, (b) mean daily wind speed and mean daily global solar radiation. (Source: Meteonorm v.7 (Meteotest, 2014), period 1964–1990)

The independent environmental variables that affect the outdoor thermal comfort are air temperature, mean radiant temperature (T_{mrt}), humidity and wind speed.

6.3.1 *Air temperature*

Tropical warm-humid climates are characterized by moderately high temperatures throughout the year and diurnal variations are typically less than 10°C, see Fig. 6.1a.

6.3.2 *Mean radiant temperature* (T_{mrt})

In the tropics the solar radiation is strong in general. Due to the high presence of clouds a great part of the radiation comes as diffuse. However, in spite of a high amount of cloud cover there are periods of clear skies, even during rainy periods.

Unlike direct beam radiation, whose direction depends on the position of the sun, diffuse radiation comes from the entire sky vault. Figure 6.2 shows the solar radiation in Dar es Salaam, Tanzania. On average, the diffuse component is slightly higher than the direct one.

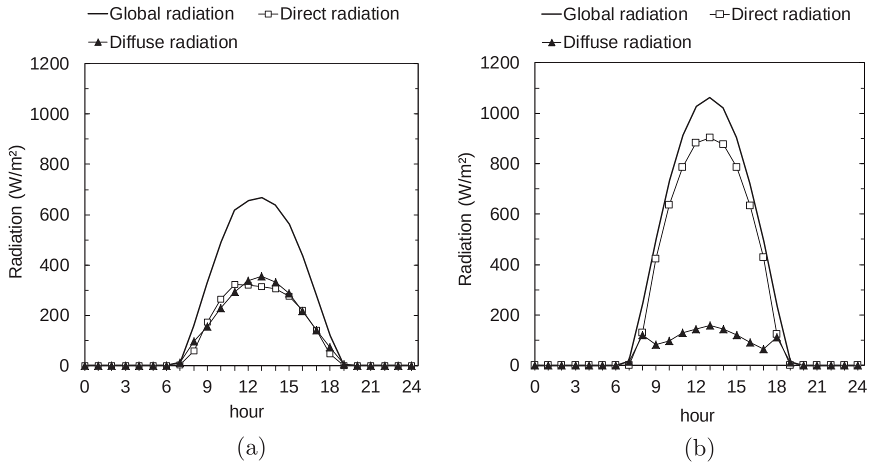
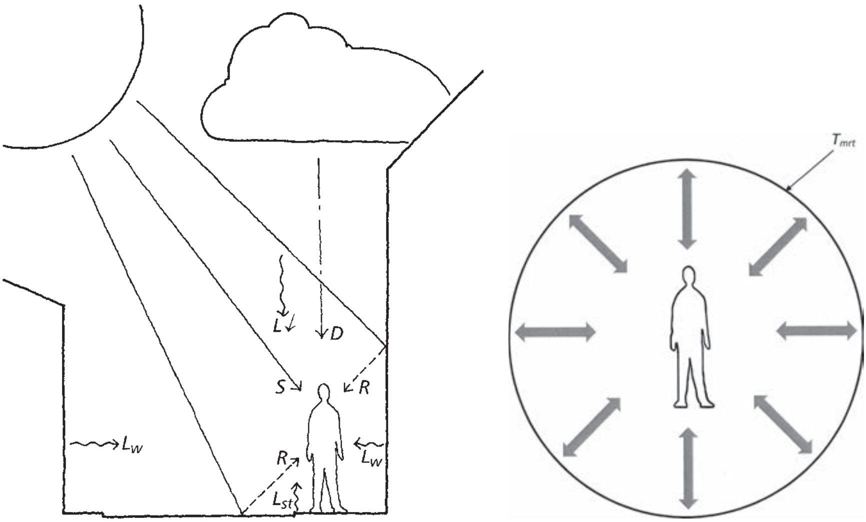


Figure 6.2. Solar radiation in Dar es Salaam, Tanzania. (a) Yearly average, (b) a clear day. (Source: Meteonorm (Meteotest, 2014))

However, on clear days the direct component dominates and the global (total) radiation reaches very high values.

In an urban area a person is exposed to high levels of radiation, not only from the sun (short-wave radiation) but also from heated surfaces (long-wave radiation), see Fig. 6.3a. The different surfaces around a person — for example a wall, a street, a window etc. — have different radiant temperatures. The short-wave radiation from the sun — either direct, diffuse or reflected — as well as the long-wave radiation from different surfaces can be combined into the T_{mrt} which is the uniform surface temperature of an imaginary black enclosure with which a person exchanges the same heat by radiation as in the actual environment (Spagnolo and de Dear, 2003), Fig. 6.3b. A T_{mrt} lower than the body surface temperature, e.g. in the open outdoors at night, leads to a net heat loss, whereas a T_{mrt} higher than the body temperature leads to a net heat gain.

The magnitude of the T_{mrt} is strongly linked to the exposure to solar radiation. At clear sky conditions the T_{mrt} may be almost twice as high compared to overcast conditions. Figure 6.4 shows how the T_{mrt} may vary with changing weather conditions.



(a) (b)

Figure 6.3. (a) A person in a street canyon exposed to direct (S), diffuse (D) and reflected (R) short-wave radiation as well as long-wave radiation from the sky ($L \downarrow$) and the urban surfaces (L_w and L_{st}) (Johansson, 2006). (b) The concept of the mean radiant temperature (T_{mrt}): a person within an enclosure whose temperature equals T_{mrt}.

6.3.3 *Humidity*

Warm-humid climates are characterized by both fairly high levels of air temperature and high levels of relative humidity. This results in high values of absolute humidity, specific humidity and vapor pressure. The yearly variation of vapor pressure for the city of Dar es Salaam is shown in Fig. 6.1a. The vapor pressure is higher during the rainy season. Table 6.1 shows minimum and maximum vapor pressures for some warm-humid cities. The diurnal variation of vapor pressure in urban areas tends to be fairly stable although there is normally a drop during the night and an increase in the late morning (Emmanuel and Johansson, 2006).

The combination of high temperature and humidity is experienced as uncomfortable since cooling of the body through evaporation is restricted. High levels of humidity also leads to a greater portion

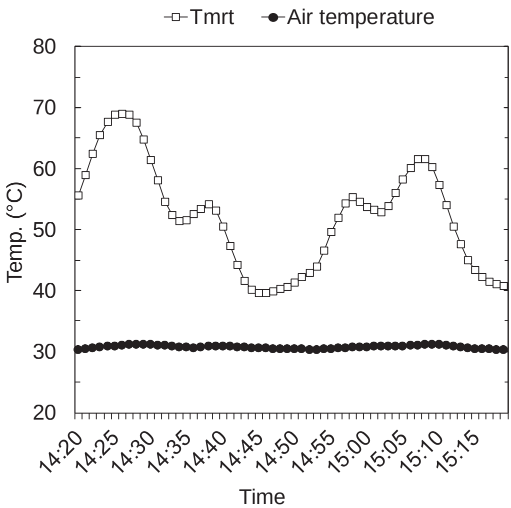


Figure 6.4. Variation of the mean radiant temperature (T_{mrt}) with cloud cover in Guayaquil, Ecuador. The air temperature, which is basically constant at 30°C, is included as reference. The higher values of T_{mrt} (around 70°C) occurred when the sky was almost clear whereas the lower values (around 40°C) represent overcast sky. (Measurements on 31 March 2010 by the author)

Table 6.1. Minimum and maximum monthly mean vapor pressure in the warm-humid cities of Colombo, Sri Lanka, Guayaquil, Ecuador and Dar es Salaam, Tanzania. (Source: Emmanuel and Johansson, 2006; Meteotest, 2014)

	Vapor pressure (hPa)	
City	Minimum	Maximum
Colombo, Sri Lanka	28	32
Dar es Salaam, Tanzania	23	31
Guayaquil, Ecuador	22	27

of skin wettedness, which increases discomfort due to the feeling of moisture and increased friction between the skin and the clothes worn (ASHRAE 2001). Givoni (1998) suggests that for people adapted to warm-humid conditions the upper vapor pressure comfort limit is about 27 hPa. This value is exceeded in many warm-humid areas (see Table 6.1).

6.3.4 *Wind speed*

The wind speed has a positive effect on thermal comfort in warm climates since it increases the convective heat loss. However, tropical areas are often characterized by low wind speeds, especially when they are affected by the intertropical convergence zone (ITCZ). This zone, also called the doldrums, which is where the trade winds come together, moves around the equator depending on the season (see Fig. 2.1). Outside the ITCZ, trade winds, monsoon winds and tropical cyclones may occur. Urban areas are especially problematic since wind speeds may be only 25–50% of the wind speed in the surrounding rural areas.

Several formulas to calculate the cooling effect of wind speed have been developed (see e.g. Emmanuel, 2005a, as well as Chapter 4 of this book). The effect depends on the humidity of the air; the higher the relative humidity, the lower the cooling effect (see

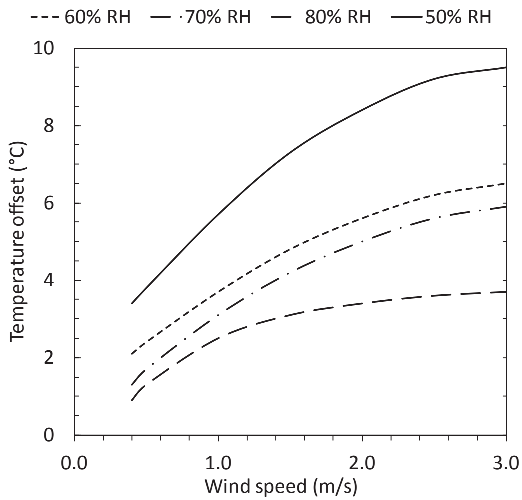


Figure 6.5. The cooling effect of the wind at different levels of relative humidity. (Source: modified after Khedari *et al.*, 2000)

Table 6.2. Effect of wind speed on the human body. (Source: modified after Penwarden, 1973)

Wind speed (m/s) at pedestrian level*	Effect on humans
0–1.1	No effect
1.2–2.5	Wind felt on face
2.6–4.0	Hair is disturbed, clothing flaps
4.1–5.9	Hair disarranged
6.0–8.0	Force of wind felt on body
8.1–10.3	Umbrellas used with difficulty, difficult to walk steadily

*i.e. the wind speed at 2 m height which is assumed to be 75% of the wind speed at 10 m.

Fig. 6.5). Moreover, the relative effect is higher at low wind speeds; for wind speeds above about 3 m/s the additional cooling effect is minor. Besides, too high wind speeds may be experienced as annoying (disturbs the hair, difficult to read newspaper, etc.; see Table 6.2). At wind speeds above 15 m/s the wind starts to be dangerous, making people lose balance, and above 20 m/s there is a strong risk of being blown over.

6.3.5 *Activity and metabolic heat production*

The net heat production (H in Eq. (6.1)) of the human body increases with increased activity. In warm-humid climates, where heat loss is restricted, high activity levels are problematic and low activity levels are therefore recommended. Table 6.3 shows the metabolic rate of some typical activities.

6.3.6 *Clothing insulation*

Clothing increases the thermal insulation of the human body. The more clothing a person is wearing, the more the heat loss is restricted. Table 6.4 shows the thermal resistance of some common clothing ensembles. A low level of clothing is obviously advantageous in warm-humid climates. However, dress codes are strongly linked to culture and consequently clothing insulation can be fairly high in

Table 6.3. Metabolic heat production of some typical activities expressed in W/m^2 and met. The second column represents a standard person with a body surface area[2] of $1.8\,m^2 \cdot 1$ met $= 58.1\,W/m^2$. (Source: ASHRAE, 2001)

Activity	W/m^2	W	Met
Reclining	45	80	0.8
Seated (relaxed)	60	105	1.0
Standing (relaxed)	70	125	1.2
Walking about	100	180	1.7
Walking 3.2 km/h (0.9 m/s)	115	205	2.0
Walking 4.3 km/h (1.2 m/s)	150	270	2.6
Walking 6.4 km/h (1.8 m/s)	220	400	3.8
Handling 50 kg bags	235	420	4.0
Pick and shovel work	235–280	420–500	4.0–4.8
Playing basketball	290–440	520–790	5.0–7.6

Table 6.4. Thermal insulation of some typical clothing ensembles expressed in clo and thermal resistance (R). 1 clo $= 0.155\,m^2K/W$. (Source: ASHRAE, 2001)

Clothing ensemble	I_{cl} (clo)	R (m^2K/W)
Shorts + short-sleeved shirt	0.4	0.06
Trousers + short-sleeved shirt	0.6	0.09
Trousers + short-sleeved shirt + suit jacket	1.0	0.15
Trousers + T-shirt + long-sleeved shirt + long-sleeved sweater	1.0	0.16
Knee-length skirt + short-sleeved shirt + panty house	0.5	0.08
Knee-length skirt + long-sleeved shirt + full slip + panty house	0.7	0.10
Ankle-length skirt + long-sleeved shirt + suit jacket + panty house	1.1	0.17

many tropical countries. Table 6.5 shows observed clothing values in some studies in warm climates.

In Guayaquil, Ecuador the clothing insulation was found to be rather high due to a fairly conservative dress code with long trousers and sometimes even long-sleeved shirts (Johansson and Yahia, 2011).

[2]A person weighing 70 kg and having a height of 1.73 m. The body surface area increases with weight and height, see ASHRAE (2001).

Table 6.5. Observed average clothing values in some studies in warm climates.

City, country	I_{cl} (clo)	Climate type	Source
Taichung City, Taiwan (summer)	0.6	Warm-humid	Lin (2009)
Singapore	0.3	Warm-humid	Yang *et al.* (2013)
Guayaquil, Ecuador	0.5	Warm-humid	Johansson and Yahia (2011)
Hong Kong (summer)	0.45	Warm-humid	Cheng *et al.* (2012)
Lisbon, Portugal (summer)	0.4	Mediterranean	Andrade *et al.* (2011)
Damascus, Syria (summer)	0.6	Hot-dry	Yahia and Johansson (2013)

The amount of clothing was slightly lower than that found during the warm humid summer in Taiwan, but higher than Singapore and Hong Kong (see Table 6.5). In Guayaquil women tend to use slightly less clothing than men, whereas in Taiwan women wore more clothing than men (Lin, 2009). In Guayaquil, no difference in clothing between the dry and the rainy seasons was found. The reasons for fairly heavy clothing could be that there is a special dress code at work, at school etc. Another reason might be solar protection; In the Guayaquil study some people actually claimed they used long-sleeved shirt to protect the skin against the sun. In a recreational area in Guayaquil the clothing was slightly lighter, with a higher presence of shorts, sleeveless shirts and sandals also for men.

Attributes to reduce solar radiation, especially in the face, are common in tropical countries. A common protection is a hat or cap. Women may also use umbrella/parasol to protect themselves against the sun. One can also see people protecting their head by holding a notebook or briefcase against the sun.

6.3.7 *Other factors influencing thermal comfort and stress*

Other factors such as non-uniformity of the environment (e.g. a mixture of warm and cold surfaces), visual stimuli, age, sex and length of exposure may influence thermal comfort and stress. In the urban outdoors where thermal conditions vary greatly within short distances — sunlit surfaces are much hotter than shaded surfaces, the wind speed may vary greatly within just a few meters distance, etc. — more people are likely to feel uncomfortable than in uniform indoor environments.

As regards time of exposure, Höppe (2002) showed that it may take almost 30 minutes for the body core temperature to reach steady state when entering a warm environment and several hours when entering a cold environment.

6.3.8 *Adaptation to the thermal environment*

Adaptation can be defined as "the gradual decrease of the organism's response to repeated exposure to a stimulus" (Nikolopoulou, 2011). Thus a person exposed to hot weather conditions for a long period of time will be less affected by the heat.

Several studies have shown that the local population is thermally adapted to the climate, e.g. Ahmed (2003), Lin (2009), Johansson and Yahia (2011) and Yahia and Johansson (2013). In warm-humid Guayaquil, Johansson and Yahia (2011) found that although the PET index (see Sec. 6.4.1.3) varied between 23°C and 51°C, as many as 37% of the subjects perceived the climate as 'comfortable'.

Adaptation is often divided into physiological, behavioral and psychological aspects (Chen and Ng, 2012). However, different types of adaptation often occur simultaneously (Nikolopoulou, 2011).

Adaptive comfort models have been developed for indoors (e.g. Humphries *et al.*, 2013; ASHRAE, 2001; ASHRAE, 2004). These models relate the indoor comfort temperature to the mean monthly outdoor temperature. Adaptive models are valid for naturally ventilated buildings (i.e. without cooling or heating) and the neutral (comfort) temperature may vary between 17°C and 31°C (ASHRAE 2001).

6.3.8.1 *Physiological adaptation*

Physiological adaptation, or *acclimatization*, refers to the thermoregulatory responses of the body to heat or cold. Acclimatization to heat, which normally occurs within one to two weeks of exposure, is characterized by higher sweat rate, lower core body temperature and lower heart rate (McIntyre, 1980; Givoni, 1998). Physiological adaptation includes changes in the set point for sweating and the skin blood flow rate (see Sec. 6.2.2).

6.3.8.2 *Behavioral adaptation*

Behavioral adaptation refers to a person's adjustment to the environment and includes change of clothing, activity level, posture, rate of working, moving in space and diet. For example, using lighter clothing increases convective heat losses (C_{s} in Eq. (6.1)) and walking more slowly decreases body heat production (H in Eq. (6.1)). Several studies in warm climates have shown that the level of clothing insulation tend to decrease with increased temperatures, e.g. Nikolopoulou and Lykoudis (2006), Lin (2009), Yahia and Johansson (2013), and Pantavou *et al.* (2013).

An important strategy in warm climates is to reduce the radiant heat gain of the body (R_s in Eq. (6.1)). This can be done by moving the body from solar exposure to shade, and by moving the body away from warm surfaces. Such behavior has been observed in several studies, e.g. Lin (2009) and Johansson and Yahia (2011). Another way to reduce radiative heat gain is by using a hat, parasol or other object to protect oneself against the solar radiation (see Fig. 6.6) (Lin, 2009; Lin *et al.*, 2013; Johansson and Yahia, 2011). The consumption of cold drinks is a common way of reducing the metabolic heat production during warm weather conditions (Lin, 2009; Nikolopoulou, 2011).

Another way to improve the thermal comfort in warm climates is to move from an area with low wind speed to an area with cooling breezes, thus increasing the convective heat loss C_s.

6.3.8.3 *Psychological aspects*

Psychological factors also influence how a person perceives the thermal environment and they are possibly the main explanation to the discrepancy between predicted (calculated) and subjectively

Figure 6.6. Umbrellas are commonly used as solar protection in the tropics. (Photo by the author from Guayaquil, Ecuador)

perceived thermal comfort (Knez and Thorsson, 2006; Nikolopoulou and Steemers, 2003; Nikolopoulou, 2011). Psychological factors include past experience, expectations and the degree of personal control. Cultural aspects have also been shown to influence the perception of thermal comfort (Knez and Thorsson, 2006).

An example of the effect of experience, or long-term memory, is that people who have been living in a certain climate for a long time know what to expect; they are not only physiologically adapted, but also mentally prepared. This partly explains why most people living in warm climates do not experience the climate as hot as might be expected.

However, there is also a short-term memory, or thermal history, which affects the perception of the thermal environment. This refers to the climate a person has experienced recently before entering the actual climate. One example of this is the effect of seasonal variation; the change from one season to another will be felt more in the beginning than after a while. Another example is that someone coming out from an air-conditioned building will perceive the thermal environment outdoors quite differently from someone who already has spent several hours outdoors (e.g. Yahia and Johansson, 2013). It should be noted that rapid relative changes (e.g. the difference between indoors and outdoors) are experienced much more than slow, long-term changes (e.g. seasonal changes) (Nikolopoulou, 2011).

Another psychological aspect is related to personal control, i.e. whether a person is in a place voluntarily or 'forced' to it (going to work/school, shopping etc.). Lin (2009) found that people choosing to visit a place were much more tolerant to the thermal environment than people who were forced to visit the same place. The possibility to be able to control or adjust the environment has thus an impact on perception; the more people believe they can control the environment, the more comfortable they feel (Nikolopoulou, 2011).

6.4 Evaluation of Thermal Indices for the Urban Tropics

Over the years hundreds of different thermal indices have been developed (Blazejczyk *et al.*, 2012). A thermal index is based on two or more environmental variables that affect the thermal comfort; some more complex indices also include the personal variables activity and clothing. The thermal perception can then be predicted based on measured and assessed environmental and personal variables.

Basically there are two types of thermal indices: comfort indices and stress indices. The former type is mainly used in more moderate environments whereas the latter is more commonly used in extreme environments, e.g. where warm climatic conditions are combined with heavy physical activity. However, many indices include both the comfort part and stress part (see Tables 6.6 and 6.7). For each index different ranges which correspond to different thermal perceptions are defined, e.g. a comfort zone, a light heat stress zone etc.

Thermal indices are divided into rational indices and empirical indices. The former are based on theory, often the heat balance of the human body (see Sec. 6.2.1), and they are calculated through

Table 6.6. 'Original' relationship between thermal perception and the indices PET, PT, SET* and UTCI. (Sources: Blazejczyk *et al.*, 2012, 2013; Bröde *et al.*, 2012; McIntyre, 1980; Matzarakis *et al.*, 1999; Staiger *et al.*, 2012)

PET (°C)	PT(°C)	SET* (°C)	UTCI (°C)	Thermal perception	Thermophysiological stress
			<−40	Frosty	Extreme cold stress
<4	≤ −39		–40 to –27	Very cold	Very strong cold stress
4–8	–39 to –26	10.0–14.5	–27 to –13	Cold	Strong cold stress
8–13	–26 to –13	14.5–17.5	–13 to 0	Cool	Moderate cold stress
13–18	–13 to 0	17.5–22.2	0 to 9	Slightly cool	Slight cold stress
18–23	0 to 20	22.2–25.6	9 to 26[a]	Comfortable	No thermal stress
23–29	20 to 26	25.6–30.0		Slightly warm	Slight heat stress
29–35	26 to 32	30.0–34.5	26 to 32	Warm	Moderate heat stress
35–41	32 to 38	34.5–37.5	32 to 38	Hot	Strong heat stress
>41	≥38	>37.5	38 to 46	Very hot	Very strong heat stress
			>46	Sweltering	Extreme heat stress

[a]The thermal comfort zone of UTCI is also referred to as 18–26°C (Bröde *et al.*, 2012a). There is no 'slightly warm' defined for this index.

advanced equations. The latter are based on empirical studies where the relationship between different variables has been determined statistically, e.g. through regression analysis.

6.4.1 *Rational indices*

Most rational indices are expressed as an equivalent air temperature in °C of a reference environment that gives the same physiological response of a reference person as the actual environment (Blazejczyk *et al.*, 2012). The advantage with the rational indices is that they take all environmental variables that affect thermal comfort — air temperature, humidity, mean radiant temperature (T_{mrt}) and wind speed — into account. A disadvantage with these indices is that they require meteorological data that is not always available, e.g. the T_{mrt}. Moreover, the measurement of the T_{mrt} and wind speed requires special equipment (see Sec. 6.5). A further problem using heat balance models outdoors is that the body may not be in equilibrium with the surrounding environment if too short a time has been spent outdoors

(Höppe, 2002). This is, however, a bigger problem in cold than in warm climates.

6.4.1.1 *Predicted mean vote (PMV) and perceived temperature (PT)*

The predicted mean vote (PMV) is a rational index based on the heat balance equation of the human body (McIntyre 1980, ASHRAE 2001). The index, which is aimed for indoor applications, takes into account the four environmental variables that affect thermal comfort as well as activity and clothing. However, in its original form introduced by Ole Fanger in the 1970s, the heat balance equation of the PMV index assumes that all sweat is evaporated. Consequently the water permeability of clothing is not taken into account, which is true only for typical indoor clothing and activity levels (ASHRAE 2001). The PMV index is also limited to steady-state conditions, i.e. no heat storage occurs. This is often not possible to achieve outdoors, especially if the time spent outdoors is short or if the weather conditions are changing rapidly (Höppe, 2002). PMV is expressed on a scale equal to a 7-point thermal perception scale (ISO 10551, 1995; ASHRAE 55, 2004) (see Sec. 6.5.2).

The PMV index is used to calculate the percentage of the people who are dissatisfied (PPD) where PPD is defined as those not voting –1, 0 or +1 on the thermal perception scale (ASHRAE, 2001) (see Sec. 6.5.2).

PMV, which is the index used in the international standard for thermal environments ISO 7730 (2005), is one of the most used thermal indices. Although the index was designed for moderate indoor environments characterized by thermal comfort or slight heat stress, it has been used in several outdoor studies (Johansson *et al.*, 2014). However, several studies have shown that in general the correlation with subjective comfort votes has been poor (e.g. Nikolopoulou *et al.*, 2001; Thorsson *et al.*, 2004) and that during warm weather conditions the index tends to overestimate thermal perception; it has been found that calculated PMV often becomes very high, far above the upper limit (+3 = hot) for which the index has been designed (e.g. Cheng *et al.*, 2012; Yahia and Johansson, 2013). The reason for this may be that skin temperature and evaporative heat loss are limited to near comfort conditions and the fact that it is a steady-state index and thus cannot handle swift changes of the thermal environment which are common outdoors.

The perceived temperature (PT) is an adaptation of the PMV index to outdoor conditions. This is made using the Klima–Michel model, a heat budget model which includes an improved model to calculate latent heat fluxes developed by Gagge *et al.* (1986) (Staiger *et al.*, 2012). This modification has increased the humidity sensitivity under warm conditions considerably (Blazejczyk *et al.*, 2012). The index, which is converted into a scale in °C to make it easier to interpret, is used by the German Meteorological Service as well as in the German guideline VDI (VDI, 2008). The relation between PT and thermal perception is shown in Table 6.6.

The clothing level of PT depends on the thermal environment; it is calculated by iterating clothing levels between 0.5 and 1.75 clo until PMV is close to zero. The metabolic rate is a constant value of 135 W/m^2 (2.3 met).

PT has not been used in many studies in the tropics, but a study in sub-tropical Sidney (Spagnolo and de Dear, 2003) and the index comparison by Blazejczyk *et al.* (2012) show that the PT performs in a similar way to other rational indices such as PET and SET*.

6.4.1.2 *Standard effective temperature (SET*)*

The standard effective temperature (SET*) is a rational index that, like PMV and PT, includes the four environmental variables that affect thermal comfort as well as activity and clothing. The index uses the so-called two-node model (Gagge *et al.*, 1986; ASHRAE, 2001), which divides the human body into two compartments: a core cylinder surrounded by the skin (ASHRAE 2001). The two-node model can be used in non-steady-state conditions to predict thermal responses for moderate activities in cool to very hot environments. SET* is thus possible to use in tropical climates. The index, which is expressed in °C, uses skin temperature and skin wettedness to define the thermal state. A simpler version of SET*, the effective temperature (ET*) (ASHRAE, 2001), also makes use of the two-node model but is restricted to typical indoor environments with standard clothing and activity (ASHRAE comfort standard 55) and has seldom been used in outdoor studies.

SET* represents the temperature of a standard environment at 50% relative humidity for subjects wearing clothing standardized for the given activity in the real environment. In this standard environment, the same skin temperature and skin wittedness exist as in the real environment (Gagge *et al.*, 1986). Table 6.6 shows the 'original' relationship between SET* and thermal perception (McIntyre, 1980).

In outdoor applications SET* is sometimes referred to as OUT_SET*, a denomination introduced by Pickup and de Dear (2000) who suggested a method to calculate T_{mrt} outdoors.

6.4.1.3 *Physiologically equivalent temperature (PET)*

The physiologically equivalent temperature (PET) is a rational index based on the heat balance of the human body (Höppe, 1999). It is based on standard clothing (0.9 clo) and activity (80 W) typical for indoors.

PET, which is expressed in °C, takes into account the four environmental variables that affect thermal comfort. It is defined as the air temperature at which the energy balance for typical indoor conditions is balanced with the same mean skin temperature and sweat rate as calculated for the complex outdoor conditions (Höppe, 1999). Table 6.6 shows the 'original' relationship between PET and thermal perception proposed by Matzarakis *et al.* (1999). This relationship has not been defined based on subjective comfort votes from field surveys; instead it has been derived by calculating PMV for a variety of air temperatures in the reference environment of the PET index using the settings for the reference person.

PET is one of the mostly used thermal indices in outdoor thermal comfort studies, especially in recent years (Johansson *et al.*, 2014). It has also been used in several studies in warm-humid climates (e.g. Emmanuel *et al.*, 2007; Lin, 2009; Johansson and Yahia, 2011; Cheng *et al.*, 2012; Ng and Cheng, 2012; Ndetto and Matzarakis, 2013). Although the index is based on indoor clothing and activity, it is suitable to predict thermal comfort conditions in warm-humid climates if the level of activity is moderate.

6.4.1.4 *Universal thermal climate index (UTCI)*

The universal thermal climate index (UTCI), which is expressed in °C, is the most recently developed thermal index based on the heat balance equation of the human body (Eq. (6.1)). It is an outdoor index that was developed to be valid in all climate types and in all seasons of the year (Jendritzky *et al.*, 2012). The relationship between UTCI and thermal perception is shown in Table 6.6.

The UTCI for a given combination of wind speed, radiation, humidity and air temperature is defined as the air temperature of the reference environment, which according to the model produces an equivalent dynamic physiological response (Bröde *et al.*, 2012a). It should be noted that whereas the other thermal indices described in this chapter use the wind speed at pedestrian height, the UTCI is based on wind speed at 10 m height. Wind measurements at pedestrian height thus need to be converted to 10 m height, using for example Eq. (6.6).

UTCI uses a detailed multi-node and multi-segmental thermophysiological model (Fiala *et al.*, 2012). The index also uses an advanced clothing model (Havenith *et al.*, 2012) where the clothing insulation depends on the ambient temperature; the lower the temperature, the higher clothing value. However, it should be noted that the relationship between temperature and clothing insulation used in UTCI is based on observations in Europe; thus, clothing habits from other cultures are not considered. Moreover, the clothing level is independent of the other environmental variables, i.e. humidity, radiation and wind speed. For example, a person in a hot-dry climate is assumed to have the same level of clothing as a person in a warm-humid climate at the same temperature. Another feature of the clothing model is that the insulation properties and vapor resistance of the clothing depend on wind speed and the air movement induced by walking is taken into account.

The metabolic rate used in UTCI is the same as for PT, i.e. a constant value of 135 W/m^2 (2.3 met), which corresponds to walking at a speed of 1.1 m/s (4 km/h). The fact that the value is fixed means that adaptive measures such as walking faster in a cold climate and slower in a warm climate are not considered. This means that in a warm climate the calculated UTCI is higher than in reality.

Since UTCI is rather new there are yet few thermal comfort studies reported from warm-humid climates. However, the index was used in a study in subtropical Curitiba, Brazil (Bröde *et al.*, 2012b), and in Mediterranean Greece (Pantavou *et al.*, 2013). Whereas UTCI was able to predict the thermal perception fairly well in Curitiba, the discrepancy between actual and predicted TP was significant in Athens and Pantavou *et al.* (2013) therefore suggested an alternative Mediterranean scale for UTCI.

6.4.2 *Empirical indices*

6.4.2.1 *Comfort indices based on linear regression equations*

Another way to predict the thermal perception is through indices based on multiple regression between subjective thermal perception votes and measured meteorological variables that influence thermal comfort (typically air temperature, humidity, solar radiation and wind speed). Such indices have been developed by several authors (e.g. Givoni *et al.*, 2003; Monteiro and Alucci, 2011; Krüger and Rossi, 2011) and are often expressed as the thermal perception scale (see Sec. 6.5.2). For sub-tropical São Paulo, with warm-humid summers, Monteiro developed the index temperature of equivalent perception (TEP) (Monteiro and Alucci, 2011):

$$TEP = -3.777 + 0.4828T_a + 0.5172T_{mrt} + 0.0802RH + 2.322V_a, \quad (6.2)$$

where T_a is the air temperature (°C), T_{mrt} is the mean radiant temperature (°C), RH is the relative humidity of the air and V_a is the wind speed (m/s). The TEP index, which is expressed in °C, is based on a questionnaire survey answered by 1750 persons in São Paulo in both summer and winter.

6.4.2.2 *Wet-bulb globe temperature* (*WBGT*)

The wet-bulb globe temperature (WBGT) is an empirical heat stress index (ASHRAE, 2001; ISO 7243, 1989). This index is the most commonly used heat stress index and has wide applications in occupational health studies of working environments, both indoors and outdoors. In the outdoors the index is calculated as

$$WBGT = 0.7T_{nw} + 0.2T_g + 0.1\mathrm{T_a}, \tag{6.3}$$

where T_{nw} = naturally ventilated wet-bulb temperature (exposed to the sun), T_g = globe temperature (exposed to the sun) and T_a = air temperature (in a radiation shield).

The globe thermometer should have a thin, matte black 150 mm globe (Parsons, 2006). Since the globe temperature depends on both radiation and air temperature (see micrometeorological measurements in Sec. 6.5) and since the T_{nw} depends on the humidity and temperature of the air, the WBGT index takes all four environmental factors that affect thermal comfort and stress into account. Except for the air temperature, the WBGT requires special equipment to be calculated, namely a globe thermometer and a naturally ventilated (non-aspirated) and non-shielded wet-bulb thermometer. The WBGT index is expressed in °C. The heat stress limits applied by WBGT are shown in Table 6.7.

Table 6.7. Reference values (upper limits) of the WBGT index for different activities for persons that are acclimatized as well as not acclimatized to heat. The values concern outdoor environments with a wind speed above 0.15 m/s. (Sources: ISO 7243, 1989; Emmanuel, 2005a)

Activity (Metabolic rate, M [W])	WBGT reference values (°C)	
	Acclimatized	Not acclimatized
Resting, sitting quietly ($M < 117$)	33	32
Standing, walking slowly ($117 < M \leq 234$)	30	29
Normal walking ($234 < M \leq 360$)	28	26
Walking fast, light work ($360 < M \leq 468$)	26	23
Heavy work ($M > 468$)	25	20

6.4.2.3 *Temperature–humidity index and heat index*

The temperature–humidity index (THI) is an empirical index developed in the USA in the 1950s to assess discomfort in warm-humid conditions (McIntyre, 1980). The index can be calculated as (Emmanuel, 2005b)

$$\mathrm{THI} = 0.8T_a + \frac{RH \times T_a}{500}, \tag{6.4}$$

where T_a (°C) is the air temperature and RH is the relative humidity in percent. The suggested comfort limits are as follows (Emmanuel, 2005b):

$21 \leq \mathrm{THI} \leq 24$: 100% of the subjects feel comfortable;
$24 < \mathrm{THI} \leq 26$: 50% of the subjects feel comfortable;
$\mathrm{THI} > 26$: 100% of the subjects feel uncomfortably hot.

The advantage with THI is that its calculation only requires temperature and relative humidity, two commonly available meteorological variables that are also easy to measure. However, neither radiation nor wind speed, two parameters that greatly affect thermal comfort, especially in the outdoors, are included and thus the index has a limited use.

The heat index (HI), or apparent temperature, is an empirical thermal index, which also depends exclusively on the air temperature and the relative humidity. The index, which is used by the National Oceanic and Atmospheric Administration (NOAA) of the USA, represents the temperature the body feels when heat and humidity are combined and is calculated according to the following formula (Blazejczyk *et al.*, 2012):

$$\begin{aligned}\mathrm{HI} = {} & -8.784695 + 1.61139411 \times T_a + 2.338549 \times RH - 0.14611605 \\ & \times T_a \times RH - 1.2308094 \times 10^{-2} \times T_a^2 - 1.6424828 \times 10^{-2} \\ & \times RH^2 + 2.211732 \times 10^{-3} \times T_a^2 \times RH + 7.2546 \times 10^{-4} \\ & \times T_a \times RH^2 - 3.582 \times 10^{-6} \times T_a^2 \times RH^2, \end{aligned} \tag{6.5}$$

where T_a (°C) is the air temperature and RH is the relative humidity in percent. Table 6.8 shows the assessment scale of the index.

The HI is only valid for temperatures above 20°C.

Table 6.8. Assessment scale of the heat index. The values concern long exposure (days) or heavy physical activity. (Source: Blazejczyk *et al.*, 2012)

Category	HI values (°C)
Caution	27–32
Extreme caution	32–41
Danger	41–54
Extreme danger	≥54

6.4.3 *Comparison of indices*

It is not evident which thermal index is best suited for outdoors in the tropics. Rational indices are recommended since they include all variables which influence thermal comfort. Some indices derived through regression analysis, such as the TEP index described in Sec. 6.4.2.1, may also include all these variables, but one should keep in mind that they are place-specific and may have limited applicability to other climates and cultures. Blazejczyk *et al.* (2012) did a comparison of the performance of various thermal indices, both advanced rational and simpler empirical, using data sets from different climate types including warm-humid. The comparison showed that all the rational indices, SET*, PET, PT and UTCI, performed well and were highly correlated. On the other hand the WBGT index and the HI did not correlate very well with these more advanced rational indices.

Many argue that the PMV index, which requires steady-state conditions and does not include the vapor resistance of clothing, is less suitable in the outdoors. As mentioned in Sec. 6.4.1.1, studies performed in the outdoors have shown that predicted PMV often is far outside the scale of the index. The PT, which is related to PMV but has been adapted for outdoor use, has not been much used in warm-humid climates but is likely to perform well.

UTCI is without doubt the most advanced rational thermal index. For example, different segments of the body are treated differently, the effect of wind speed on clothing insulation is taken into account and the clothing value depends on the outdoor temperature. Compared to PET, whose reference environment is an indoor environment, UTCI has the advantage of having an activity (walking) that is more adapted to outdoor conditions. Consequently, UTCI is more likely to correctly predict the thermal conditions than PET in different climates. On the other hand, in its present version the model does not seem to be perfectly adapted to warm-humid climates. For example, the activity (walking at 1.1 m/s speed) is quite high and the clothing values are unrealistically low at high temperatures, especially above 31°C (Pantavou *et al.*, 2013). So far the UTCI has not been used in many warm-humid studies, but this is mainly due to the fact that the index is rather new.

Although PET is a fairly simple index where activity and clothing values are fixed and whose reference environment is a typical indoor environment, it has proven to work well in warm-humid climates, perhaps because the clothing and activity (sitting) of PET are similar to what can be found in warm-humid climates. PET is currently the most commonly used index in outdoor thermal comfort studies including those in warm-humid climates.

SET* (or OUT_SET*) is also less advanced than UTCI. The advantage of SET* compared to both UTCI and PET, however, is that actual observed values (or standard values) of clothing insulation and metabolic rate can be used. SET* has been used in a great number of outdoor thermal comfort studies, many of which have been performed in warm-humid climates.

In general it is often an advantage to use a well-established index that has been used in other studies in order to be able to compare results. It may also be worthwhile using several indices.

Whatever the index chosen, most studies show that the thermal perception scale of any thermal index varies from one climate type to another. In climates with distinct seasons, e.g. summer and winter, the perception scale is normally different between these seasons. Several studies show that people have higher tolerance to heat in warm climates. Thus, whatever index being used it should be calibrated to the local conditions (or at least to a similar climate). For example, it is not correct to use the 'official', theoretically determined scale of the PET index shown in Table 6.6 in a warm-humid context. Examples of calibration in warm-humid climates are Lin and

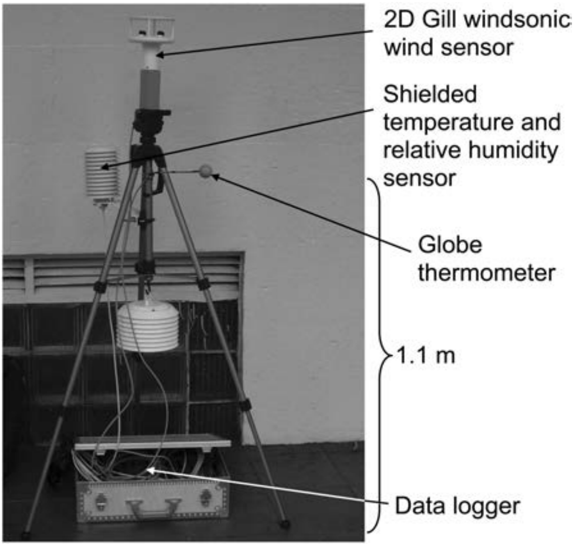


Figure 6.7. Measurement sensors mounted on a camera tripod and connected to a data logger. The wind speed has to be transformed to the height of 1.1 m using Eq. (6.6). (Source: Johansson and Yahia, 2011)

Matzarakis (2008), who proposed a different PET classification for Taiwan, and Ng and Cheng (2012) who defined a neutral PET for Hong Kong. (See also Table 6.9.)

6.5 Field Surveys — Measurements and Questionnaires

Field surveys of thermal comfort normally consist of both 'objective' measurements of meteorological variables and an investigation of the 'subjective' thermal perception of the people using the investigated space.

6.5.1 *Micrometeorological measurements*

Air temperature, relative humidity and wind speed can be measured directly. The mean radiant temperature (T_{mrt}), on the other hand, has to be either calculated from radiation measurements or modeled.

The sensors are normally mounted on a camera tripod (see Fig. 6.7) or equivalent. The most convenient is to have the sensors connected to a data logger on which 1-minute averages are sampled. The recommended heights of the sensors are 0.6 m and 1.1 m for sitting and standing subjects, respectively (ISO 7726, 1998). These heights represent the centre of gravity of the human body.

6.5.1.1 *Air temperature, humidity and wind speed*

Temperature and humidity sensors may be heated by the sun and/or warm urban surfaces. Therefore, such probes need to be properly shielded to minimize radiative exchange between the instrument and its surroundings. The shield must also be ventilated in order to avoid the formation of warm air around the sensor. If wind speeds are low, say less than 1 m/s, the radiation shield should preferably be aspirated. Due to the inertia of the sensor, one should let it reach equilibrium with the thermal environment before the measurements start (ISO 7726, 1998; Johansson *et al.*, 2014).

Since both speed and direction of the wind vary considerably in urban areas, 3D measurements (measuring both horizontal and vertical wind speeds) are recommended (Johansson *et al.*, 2014). If the wind is measured only horizontally, then the actual wind speed may be underestimated. The instrument chosen needs to have a quick response time and sufficient accuracy. If wind speeds are low, cup and propeller anemometers may not be appropriate since they typically have a threshold of about 0.5 m/s. Omni-directional hot-wire and hot-sphere anemometers can measure low wind speeds but on the other hand they have an upper wind-speed limit. Sonic anemometers are the best since they measure both low and high wind speeds accurately, but they are also the most expensive.

For practical reasons wind is often measured at a higher height than the other sensors. The corresponding wind speed at the desired height, e.g. 1.1 m, is then calculated by the so-called power law as (Aynsley, 1977; Spagnolo and de Dear, 2003):

$$v_{1.1} = v_z \times \left(\frac{1.1m}{zm}\right)^{\propto}, \tag{6.6}$$

where $v_{1.1}$ = wind speed at 1.1 m, v_{z} = wind speed at height z (m/s) and α is the mean speed exponent, which depends on the roughness of the ground (e.g. $\alpha = 0.25$ for suburbs and $\alpha = 0.36$ in the centre of large cities with high-rise buildings according to Ainsley *et al.*, (1977)).

6.5.1.2 *Mean radiant temperature* (T_{mrt})

The most accurate way to determine T_{mrt} is through simultaneous measurements of short- and long-wave radiation from six directions (east, west, north, south, upward and downward) (see e.g. Thorsson *et al.* (2007b) and Johansson *et al.* (2014)). The method requires six instruments to measure short- and long-wave radiation, respectively, which makes it expensive. Somewhat simpler methods, using only one instrument for short- and long-wave radiation respectively, are described in VDI 3787 (2008) and Spagnolo and de Dear (2003).

Another, much cheaper, method to determine T_{mrt} is by using a globe thermometer (see Fig. 6.7) combined with measurements of air temperature and wind speed (Thorsson *et al.*, 2007b; Johansson *et al.*, 2014). In the urban outdoors radiation and wind speed change rapidly. To be able to register sudden variations in T_{mrt}, the globe should be of small size and have a low heat capacity in order to reduce its response time. Globe thermometers exposed to solar radiation should have a medium grey color to represent the outer surface of clothed persons (ISO 7726, 1998; ASHRAE, 2001). Thorsson *et al.* (2007b) found that a flat grey (RAL 7001) painted table tennis ball (Ø = 40 mm) containing a pt100 temperature sensor gives accurate results, although it slightly overestimates T_{mrt} during shady conditions and slightly underestimates it during sunny conditions. Calibration with short- and long-wave radiation measurements yielded the following formula:

$$T_{mrt} = \left[(T_g + 273.15)^4 + \frac{1.335 \times 10^8 V_a^{0.71}}{\varepsilon D^{0.4}}(T_g - T_a)\right]^{0.25} - 273.15, \tag{6.7}$$

where T_g is the globe temperature (°C), V_a is the wind speed (m/s), T_a is the air temperature (°C), D is the globe diameter = 0.04 m, and ε is the globe emissivity = 0.97.

The formula in Eq. (6.7) is very sensitive to rapid changes in wind speed and therefore the average wind speed over a sufficiently long period — at least 5 minutes — should be used (Thorsson *et al.*, 2007b).

The standard globe thermometer used indoors — which is matte black painted with a diameter of 150 mm, often made of copper — is not suitable outdoors since such a large and heavy instrument may take 20–30 min to reach equilibrium (Spagnolo and de Dear, 2003; Johansson *et al.*, 2014).

It should be noted that the formula in Eq. (6.7) was derived for latitude 57°; ideally the formula should be determined through calibration with integral radiation measurements (as described above) at each geographical location or at least for a similar climate zone and latitude.

T_{mrt} can also be estimated using models such as RayMan (Matzarakis *et al.*, 2010), SOLWEIG (Lindberg *et al.*, 2015) and ENVI-met (Bruse, 2015). Such modeling requires either measurements or simulations of solar radiation as well as modeling of the urban morphology (buildings, trees etc.).

6.5.2 *Questionnaire surveys on subjective thermal perception*

Thermal perception can be assessed through field surveys where the subjective opinion of a group of people is studied. These surveys normally use questionnaires containing judgment scales where people are asked how they perceive the actual thermal environment they are exposed to.

Subjects are normally asked to report their thermal perception on a 7- or 9-point scale in accordance with ISO 10551 (1995). The typical question is "How do you feel right now?". The 7-point scale, often referred to as the ASHRAE scale, is the most commonly used indoors and is often used outdoors as well. Since outdoor conditions vary greatly and are more extreme, it may be motivated to use a 9-point scale (ISO 10551, 1995; Thorsson *et al.* 2007a; Yahia and Johansson, 2013). Some researchers, however, have argued that it is difficult for the interviewee to give an answer with such precision and some studies have therefore used a 5-point scale (e.g. Nikolopoulou and Lykoudis, 2006). The 9-point scale consists of the following points: very cold (–4), cold (–3), cool (–2), slightly cool (–1), neutral (neither warm nor cool) (0), slightly warm (+1), warm (+2), hot (+3), and very hot (+4). The 7-point scale is identical except that the extreme values very cold (–4) and very hot (+4) are not included. In warm-humid climates there will be a bias towards the warm side of the scale and votes below slightly cool (–1) will be rare.

People's thermal preference at different climatic conditions is often reported on a 3-point scale (sometimes called the McIntyre scale). The subjects are asked whether they would like it to be cooler, no change or warmer. The preference may also regard solar radiation/shade, humidity and wind speed.

Apart from thermal perception and preference the questionnaire often includes general questions about the subject such as gender and age. Other common questions relate to thermal history, e.g. the reason for being in the place and time spent outdoors. The type of clothing and activity should be observed by the interviewer. The clothing is preferably chosen from a pre-defined list and the activity can normally be divided into sitting, standing or walking.

The questionnaire should preferably be translated into the local language. Here the wording is of importance to guarantee a correct interpretation; preferably an official translation should be used. ISO 10551 (1995) contains subjective thermal perception scales in English, Spanish, French and Russian. The team carrying out the interviews should preferably be the same throughout the survey. The interviewees should be picked randomly, regardless of age, gender, ethnic origin, etc. A questionnaire survey normally goes on for about 1–3 hours. For each interview the time should be noted at the beginning of the interview. An interview may take about 1–5 minutes to complete depending on the amount of questions. It should be emphasized by the interviewers that it is the subjects' judgment at the moment of the interview that is requested and not their general opinion. The adequate total sample size is difficult to specify but may be 400–500 persons and should include a good balance of age and gender and a distribution of the interviewees over time (to cover diurnal and seasonal changes) (Johansson *et al.*, 2014).

6.6 Assessment of Thermal Comfort

Field surveys with simultaneous measurements and questionnaire campaigns can be used to calibrate thermal indices — i.e. to define the limits for thermal comfort and different levels of thermal stress — as well as to determine neutral and preferred temperatures. Such studies should be carried out at different times of the day — e.g. morning, early afternoon and evening — in order to cover a variety of thermal conditions. This will enable a larger spread of thermal perception votes, which is necessary to get votes on both the cold and the warm sides of the neutral index temperature in order to be able to define the thermal comfort zone.

6.6.1 *Thermal comfort zones*

It has been shown in several studies, both indoors and outdoors, that people may feel comfortable although a thermal index would indicate that the environment is not comfortable. As discussed in Sec. 6.3.8, this is due to physiological, behavioral and psychological adaptation. The perception scale of the chosen index thus should be calibrated to the local conditions. The actual subjective thermal comfort can be estimated through a questionnaire survey performed simultaneously with micrometeorological measurements at each location.

Normally, votes within the three central categories (–1, 0 and +1) of the thermal perception scale show satisfaction with the thermal environment whereas votes below –1 and above +1 show the contrary, i.e. dissatisfaction (e.g. ASHRAE, 2001; Spagnolo and de Dear, 2003; Lin, 2009). Figure 6.8 shows an example of the relationship between a thermal index (PET) and the percentage of people being dissatisfied. Thermal comfort is then defined as the lower and upper limits of the index temperature in between which a certain percentage, typically 80%, are satisfied.

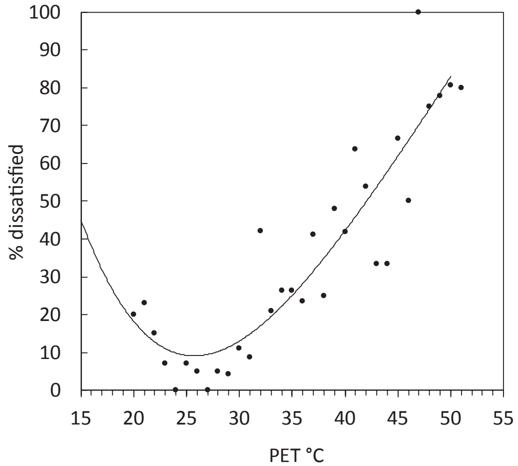


Figure 6.8. Example of the relationship between the percentage of dissatisfied and PET. If thermal comfort is defined as the range within which 80% of the people are satisfied (20% dissatisfied), then the thermal comfort zone of this example can be defined between PET values of about 20°C and 33°C. (Source: Author)

Table 6.9 shows the comfort zones for PET for some studies in warm and humid climates. It can be concluded that the local population accepts much higher PETs than in the 'original' thermal perception scale of PET for a temperate climate (see Table 6.6).

6.6.2 *Neutral and preferred temperatures*

The index temperature found to coincide with the thermal perception vote 0 (neutral or 'not cool nor warm') is referred to as the neutral temperature. To determine the neutral temperature, simple linear regression can be used. With this method the neutral temperature is defined as the intersection between the regression line and the vote 0 (see Fig. 6.9). However, as pointed out by Ballantyne *et al.* (1977), the relationship between thermal perception votes and the index temperature is not necessarily linear. Several studies, e.g. Lin (2009), Lin *et al.* (2011), Kántor *et al.* (2012) and Yahia and Johansson (2013), have shown that the regression line of the PET index tends to have a lower slope at higher index temperatures. In

Table 6.9. Comfort limits, neutral temperatures and preferred temperatures for the PET index from studies in warm-humid and similar climates.

Geographical location	Season	Comfort zone (°C)	Percentage of satisfaction	Neutral index tempera-ture (°C)	Preferred index tempera-ture (°C)	Source
Hong Kong	Summer	n/a	n/a	28.1	n/a	Ng and Cheng, 2012
Taichung, Taiwan	Summer and winter	21.3–28.5	90%	25.6	24.5	Lin, 2009
Sun Moon Lake, Taiwan	Summer and winter	24.2–32.8	85%	27.2	n/a	Lin and Matzarakis, 2008
Sydney, Australia	Summer	n/a	n/a	22.9	23.4	Sagnolo and de Dear, 2003
Tel Aviv, Israel	Summer	20–26	80%	23.9	n/a	Cohen *et al.*, 2013

n/a = not available

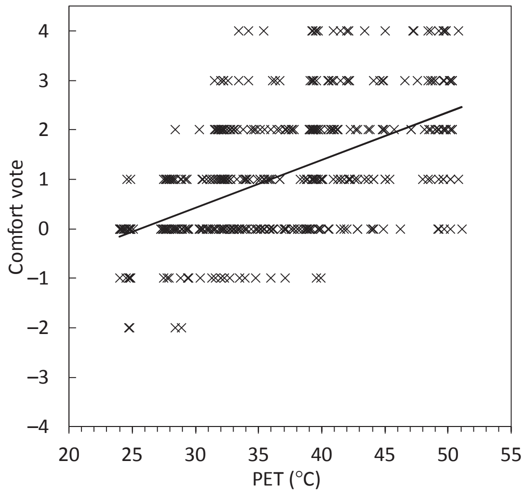


Figure 6.9. The relationship between the PET index and the thermal perception votes in Guayaquil, Ecuador (+4 = very hot, +3 = hot, +2 = warm, +1 = slightly warm, 0 = neutral, −1 = slightly cool, −2 = cool, −3 = cold, −4 = very cold). The total number of votes was 544. Linear regression gives a neutral PET of 25.6°C. (Source: Johansson and Yahia, 2011)

such situations probit analysis (Ballantyne *et al.*, 1977) can be used to determine T_n. With this method all thermal perception votes are divided into two groups: cooler than neutral (<0) and warmer than neutral (>0). The votes equal to 0 are split randomly between the two groups. The neutral temperature is then determined as the index temperature at which 50% of the sample voted cooler than neutral and 50% voted warmer than neutral. A statistical program can be used to perform the probit analysis.

Figure 6.9 shows an example of the relationship between thermal perception votes and PET. Although there is a clear trend that the environment is perceived as warmer with increasing index temperature, there is a wide spread in the votes. For example, at 40°C PET the thermal perception varies between slightly cool (–1) to very hot (+4). The great variety in thermal perception is due to individual differences as well as factors related to physiological, behavioral and psychological adaptation, as discussed in Sec. 6.3.8.

The preferred temperature is defined as the index temperature at which 50% of the sample vote that they want it to be cooler and 50% vote that they want it to be warmer (McIntyre, 1980). Since the preferred temperature is the temperature people 'actively' prefer, it may be different from the neutral temperature (Lin *et al.*, 2011) (see Table 6.9). The preferred temperature can be determined in the same way as the neutral temperature using probit analysis. Several studies have shown that in general people in warm climates perceive the climate as uncomfortably warm and they prefer lower temperatures. People also want more shade and more wind (Johansson and Yahia, 2011; Lin, 2009; Lin *et al.*, 2011, 2013; Spagnolo and de Dear, 2003; Yang *et al.*, 2013 and as shown in Chapter 3).

Table 6.9 shows the neutral and preferred temperatures from some studies in warm-humid climates. Although the values differ somewhat between the studies, it is evident that people are adapted to the local climate.

Several studies in warm-humid climates have found that the preferred temperature is lower than the neutral temperature (Lin, 2009; Lin *et al.*, 2011, Yang *et al.*, 2013). This can be explained by the fact that people in a hot environment in general would like it to be cooler; it has been explained by the phenomenon alliesthesia, which in this case would mean that if a person is feeling hot then anything that cools him/her down will feel pleasant, even if this stimulus will lead to the perception of cold in the long-term (Spagnolo and de Dear, 2003) and by the fact that people want stimulation, i.e. they want a change from a 'statically' warm or cold environment (Nikolopoulou, 2011).

References

Ahmed, K.S. (2003) Comfort in urban spaces: defining the boundaries of outdoor thermal comfort for the tropical urban environments, *Energy and Buildings*, **35**, 103–110.

Andrade, H., Alcoforado, M.J. and Oliveira, S. (2011). Perception of temperature and wind by users of public outdoor spaces: relationships with weather parameters and personal characteristics, *International Journal of Biometeorology*, **55**, 665–680.

ASHRAE (2001). *ASHRAE Handbook Fundamentals*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA.

ASHRAE Standard 55 (2004). *Thermal Environmental Conditions for Human Occupancy*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA.

Aynsley, R.M., Melbourne, W. and Vickery, B.J. (1977). *Architectural Aerodynamics*, Applied Science Publishers, London, UK.

Ballantyne, E.R., Hill, R.K. and Spencer, J.W. (1977). Probit analysis of thermal sensation assessments, *International Journal of Biometeorology*, **21**, 29–43.

Blazejczyk, K., Jendritzky, G., Staiger, H. *et al.* (2012). Comparison of UTCI to selected thermal indices, *International Journal of Biometeorology*, **56**, 515–535.

Blazejczyk, K., Jendritzky, G., Bröde, P. *et al.* (2013). An introduction to the universal thermal climate index (UTCI), *Geographia Polonica*, **86**, 5–10.

Bröde, P., Fiala, D., Błażejczyk, K. *et al.* (2012a). Deriving the operational procedure for the universal thermal climate index (UTCI), *International Journal of Biometeorology*, **56**, 481–494.

Bröde, P., Krüger, E.L., Rossi, F.A. *et al* (2012b). Predicting urban outdoor thermal comfort by the universal thermal climate index UTCI—a case study in Southern Brazil, *International Journal of Biometeorology*, **56**, 471–480.

Bruse, M. (2015). ENVI-met Model Homepage. Available at http://www.envi-met.com (accessed 27 April 2015).

Chen, L. and Ng, E. (2012). Outdoor thermal comfort and outdoor activities: A review of research in the past decade, *Cities*, **29**, 118–125.

Cheng, V., Ng, E., Chan, C. *et al.* (2012). Outdoor thermal comfort study in a sub-tropical climate: a longitudinal study based in Hong Kong, *International Journal of Biometeorology*, **56**, 43–56.

Cohen, P., Potchter, O. and Matzarakis, A. (2013). Human thermal perception of coastal Mediterranean outdoor urban environments, *Applied Geography*, **37**, 1–10.

Emmanuel, M.R. (2005a). *An Urban Approach to Climate-Sensitive Design. Strategies for the Tropics*, Spon Press, London, UK.

Emmanuel, R. (2005b). Thermal comfort implications of urbanization in a warm-humid city: the Colombo Metropolitan Region (CMR), Sri Lanka, *Building and Environment*, **40**, 1591–1601.

Emmanuel, R. and Johansson, E. (2006). Influence of urban morphology and sea breeze on hot humid microclimate: the case of Colombo, Sri Lanka, *Climate Research*, **30**, 189–200.

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**, 1995–2004.

Fiala, D., Havenith, G., Bröde, P. *et al.* (2012). UTCI-Fiala multi-node model of humanheat transfer and temperature regulation, *International Journal of Biometeorology*, **56**, 429–441.

Gagge, A.P., Fobelets, A. and Berglund, L.G. (1986). A standard predictive index of human response to the thermal environment, *ASHRAE Transactions*, **92**, 709–731.

Givoni, B. (1998). *Climate Considerations in Building and Urban Design*, Van Nostrand Reinhold, New York, NY.

Givoni, B, Noguchi, M., Saaroni, H. *et al.* (2003). Outdoor comfort research issues, *Energy and Buildings*, **35**, 77–86.

Havenith, G., Fiala, D., Błazejczyk, K. *et al.* (2012). The UTCI-clothing model, *International Journal of Biometeorology*, **56**, 461–470.

Humphreys, M.A., Rijal, H.B. and Nicol, J.F. (2013). Updating the adaptive relation between climate and comfort indoors; new insights and an extended database, *Building and Environment*, **63**, 40–55.

Höppe, P. (1999). The physiological equivalent temperature — a universal index for the assessment of the thermal environment, *International Journal of Biometeorology*, **43**, 71–75.

Höppe, P. (2002) Different aspects of assessing indoor and outdoor thermal comfort, *Energy and Buildings*, **34**, 661–665.

ISO 7726 (1998). *Ergonomics of the thermal environment — Instruments for measuring physical quantities*, International Organization for Standardization, Geneva, Switzerland.

ISO 7730 (2005). *Ergonomics of the thermal environment — Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria*, International Organization for Standardization, Geneva, Switzerland.

ISO 7243 (1989). *Hot Environments — Estimation of the heat stress on working man, based on the WBGT-index* (*wet bulb globe temperature*), International Organization for Standardization, Geneva, Switzerland.

ISO 10551 (1995). *Ergonomics of the thermal environment — Assessment of the influence of the thermal environment using subjective judgement scales*, International Organization for Standardization, Geneva, Switzerland.

Jendritzky, G., de Dear, R. and Havenith, G. (2012). UTCI — Why another thermal index?, *International Journal of Biometeorology*, **56**, 421–428.

Johansson, E. (2006). Urban Design and Outdoor Thermal Comfort in Warm Climates. Studies in Fez and Colombo, PhD Thesis, Lund University, Lund, Sweden.

Johansson, E. and Emmanuel, R. (2006). The influence of urban design on outdoor thermal comfort in the hot, humid city of Colombo, Sri Lanka, *International Journal of Biometeorology*, **51**, 119–133.

Johansson, E. and Yahia, M.W. (2011). Subjective thermal comfort in urban spaces in the warm-humid city of Guayaquil, Ecuador, in Bodart, M. and Evrard, A. (eds.), *Architecture & Sustainable Development, Vol. 1*, Presses universitaires de Louvain, Lovain-la-Neuve, Belgium, 577–582.

Johansson, E., Spangenberg, J., Lino Gouvêa, M. *et al.* (2013). Scale-integrated atmospheric simulations to assess thermal comfort in different urban tissues in the warm humid summer of São Paulo, Brazil, *Urban Climate*, **6**, 24–43.

Johansson, E., Thorsson, S., Emmanuel, R. *et al.* (2014). Instruments and methods in outdoor thermal comfort studies — The need for standardization, *Urban Climate*, **10**, 346–366.

Kántor, N., Unger, J. and Gulyás, Á. (2012). Subjective estimation of thermal environment in recreational urban spaces — Part 2: international comparison, *International Journal of Biometeorology*, **56**, 1089–1101.

Khedari, J., Yamtraipat, N., Pratintong, N. *et al.* (2000). Thailand ventilation comfort chart, *Energy and Buildings*, **32**, 245–249.

Knez, I. and Thorsson, S. (2006). Influences of culture and environmental attitude on thermal, emotional and perceptual evaluations of a public square, *International Journal of Biometeorology*, **50**, 258–268.

Krüger, E.L. and Rossi, F.A. (2011). Effect of personal and microclimatic variables on observed thermal sensation from a field study in southern Brazil, *Building and Environment*, **46**, 690–697.

Lin, T.-P. (2009). Thermal perception, adaptation and attendance in a public square in hot and humid regions, *Building and Environment*, **44**, 2017–2026.

Lin, T.-P., de Dear, R. and Hwang, R.-L. (2011). Effect of thermal adaptation on seasonal outdoor thermal comfort, *International Journal of Climatology*, **31**, 302–312.

Lin, T.-P. and Matzarakis, A. (2008). Tourism climate and thermal comfort in Sun Moon Lake, Taiwan, *International Journal of Biometeorology*, **52**, 281–290.

Lin, T.-P., Tsai, K.-T., Liao, C.-C. *et al.* (2013). Effects of thermal comfort and adaptation on park attendance regarding different shading levels and activity types, *Building and Environment*, **59**, 599–611.

Lindberg, F., Thorsson, S., Holmer, B. *et al.* (2015). SOLWEIG Model Homepage. Available at http://gvc.gu.se/english/staff/staff/thorsson-sofia/current-projects/the-solweig-model (accessed 27 April 2015).

Matzarakis, A., Mayer, H. and Iziomon, M.G. (1999). Applications of a universal thermal index: physiological equivalent temperature, *International Journal of Biometeorology*, **43**, 76–84.

Matzarakis, A., Rutz, F. and Mayer, H. (2010). Modelling radiation fluxes in simple and complex environments: basics of the RayMan model, *International Journal of Biometeorology*, **54**, 131–139.

McIntyre, D.A. (1980). *Indoor Climate*, Applied Science Publishers, London, UK.

Meteotest (2014). METEONORM 7.0. Meteotest, Bern, Switzerland.

Monteiro, L.M. and Alucci, M.P. (2011). Proposal of an outdoor thermal comfort index: empirical verification in the subtropical climate, in Bodart, M. and Evrard, A. (eds.), *Architecture & Sustainable Development, Vol. 1*, Presses universitaires de Louvain, Lovain-la-Neuve, Belgium, 433–438.

Ndetto, E.L. and Matzarakis, A. (2013). Basic analysis of climate and urban bioclimate of Dar es Salaam, Tanzania, *Theoretical and Applied Climatology*, **114**, 213–226.

Ng, E. and Cheng, V. (2012). Urban human thermal comfort in hot and humid Hong Kong, *Energy and Buildings*, **56**, 51–65.

Nikolopoulou, M., Baker, N. and Steemers, K. (2001). Thermal comfort in outdoor urban spaces: understanding the human parameter, *Solar Energy*, **70**, 227–235.

Nikolopoulou, M. and Steemers, K. (2003).Thermal comfort and psychological adaptation as a guide for designing urban spaces, *Energy and Buildings*, **35**, 95–101.

Nikolopoulou, M. and Lykoudis, S. (2006). Thermal comfort in outdoor urban spaces: analysis across different European countries, *Building and Environment*, **43**, 1185–1196.

Nikolopoulou, M. (2011). Outdoor thermal comfort, *Frontiers in Bioscience*, **S3**, 1552–1568.

Pantavou, K., Theoharatos, G., Santamouris, M. *et al.* (2013). Outdoor thermal sensation of pedestrians in a Mediterranean climate and a comparison with UTCI, *Building and Environment*, **66**, 82–95.

Parsons, K. (2006). Heat stress standard ISO 7243 and its global application, *Industrial Health*, **44**, 368–379.

Penwarden, A.D. (1973). Acceptable wind speeds in towns, *Building Science*, **8**, 259–267.

Pickup, J. and de Dear, R. (2000). An outdoor thermal comfort index (OUT SET*). Part I — The model and its assumptions, in de Dear, R. *et al.* (eds.), *Biometeorology and Urban Climatology at the Turn of the Millennium*, World Meteorological Organization, Sydney, Australia, 71–98.

Spagnolo, J. and de Dear, R. (2003). A field study of thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney, Australia, *Building and Environment*, **38**, 721–738.

Staiger, H., Laschewski, G. and Grätz, A. (2012). The perceived temperature — a versatile index for the assessment of the human thermal environment. Part A: scientific basics, *International Journal of Biometeorology*, **56**, 165–176.

Thorsson, S., Lindqvist, M. and Lindqvist, S. (2004). Thermal bioclimatic conditions and patterns of behavior in an urban park in Göteborg, Sweden, *International Journal of Biometeorology*, **48**, 149–156.

Thorsson, S., Honjo, T., Lindberg, F. *et al.* (2007a). Thermal comfort and outdoor activity in Japanese urban public places, *Environment and Behavior*, **39**, 660–684.

Thorsson, S., Lindberg, F., Eliasson, I. *et al.* (2007b). Different methods for estimating the mean radiant temperature in an outdoor urban setting, *International Journal of Climatology*, **27**, 1983–1993.

VDI (2008). *VDI 3787 Part 2, Environmental Meteorology — Methods for the Human Biometeorological Evaluation of Climate and Air Quality for Urban and Regional Planning at Regional Level; Part I: Climate*, Beuth Verlag, Berlin, Germany.

Yahia, M.W. and Johansson, E. (2013). Evaluating the behaviour of different thermal indices by investigating various outdoor urban environments in the hot dry city of Damascus, Syria, *International Journal of Biometeorology*, **57**, 615–630.

Yang, W., Wong, N.H. and Jusuf, S.K. (2013). Thermal comfort in outdoor urban spaces in Singapore, *Building and Environment*, **59**, 426–435.

Chapter 7

Urban climate mapping in the tropics

Narein Perera

Urban climatology is a rapidly growing field. Standards are therefore necessary to ensure consistent and meaningful exchange of data across regions, cultures and disciplines. (Stewart *et al.*, 2014) A simple protocol for the classification of urban sites for mitigation of the negative effects of the urban heat island (UHI) phenomenon is essential for research and urban design.

For many decades the UHI effect, and therefore the intensity, has been communicated by simple comparison of temperatures between 'urban' and 'rural' sites. However, a systematic review and scientific critique of methodology in modern UHI literature by Stewart (2011a) found the results discouraging, with a significant portion of the observational heat island literature failing to adequately define qualitative metadata of the measurement site exposure or land cover.

The need for a standardized method for site classification, highlighted in Stewart's 2011 study, arose from three interrelated problems: (1) insufficient description of sites in past studies, (2) the difficulty of categorizing complex human landscapes that range from highly developed to undeveloped, and (3) the need for a standardized method to compare UHI research in different biophysical regions. (Coseo and Larsen, 2014).

The challenges to forming a comprehensive, climate-based view of urban and rural field sites encompass similar issues relating to: varying interpretation of landscape with different regions, cultures and language; sites diverse in exposure, land cover, building materials and human activities; the lack of a meaningful definition of what is 'urban' and rural', a concept deeply rooted in UHI literature; and the lack of a comprehensive site classification system that brings together both urban and rural zones (e.g. urban terrain zones (UTZ) by Ellefsen (1990–91) and urban climate zones (UCZ) by Oke (2004) do not include rural zones).

The primary objective was to find common traits in all sites and then to group traits into common classes — the local climate zone (LCZ) system. However, its use has since been enhanced to encompass a wider range of application, from remote-sensed mapping to the interpretation of social segregation. This chapter will show how LCZ delineation could be used to develop/test/propose urban planning/design strategies appropriate for each neighborhood-level context in the tropics.

7.1 Urban Climate Mapping and Local Climate Zones (LCZ)

7.1.1 *Urban climatic maps*

The pioneering applications at the urban scale emerged in German cities, termed the Klimaatlas, where a map-based methodology with documentary support was developed. Simplifying and rendering legible those aspects of the urban climate effect that are relevant to human health and comfort, the Klimaatlas offered a means of communication between scientists and decision-makers. The use of a relatively high level of resolution allowed point-specific recommendations for policy and regulation (Hebbert, 2014).

Chen and Ng (2011) describe mapping urban climatic information for planning purposes as an idea with its basic landscape developed in the 1990s in the institutional guidelines of Germany (VDI, 1997). They found that climatic mapping has been applied to a number of governmental and research projects across the world, including the Urban Climate 21 program in Stuttgart, Germany (Office for Environmental Protection, N/A); the Climatological Air Temperature Map in Poland (Ustrnul and Czekierda, 2005); the

Urban Environmental Climate Map in Japan (Tanaka *et al.*, 2009); the Bioclimatic Map in Portugal (Alcoforado *et al.*, 2009); the Local Climate Zone Map in Canada (Stewart and Oke, 2009), and the Urban Climatic Map in Hong Kong (Planning Department, 2008). Despite their different specialties and implementation methods, these projects all aim to provide visual and also analytical information for planners (Chen and Ng, 2011). Other studies trace the beginnings of urban climate mapping as far back as Chandler (1965), Auer (1978) and Ellefsen (1991).

7.1.2 *Local climate zones*

The new LCZ classification system provides a selection and reporting framework for UHI studies and standardizes the worldwide exchange of urban temperature observations (Stewart and 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.

The primary aim was;

> "Not to supplant the terms urban and rural from heat island discourse, but instead to encourage a more constrained use of these terms when describing the local physical conditions of a field site, where the terms urban and rural alone cannot sufficiently describe a field site or its local surroundings.
>
> 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 standardised 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 and Oke, 2012)

LCZs are defined as "regions of uniform surface-air temperature distribution at horizontal scales of 10^2–10^4 m" (Stewart and 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 in constructing the LCZ framework include (Fig. 7.1):

1. height of roughness features (buildings and/or vegetation);
2. packing of roughness features (buildings and/or vegetation);
3. surface cover around roughness elements; and
4. thermal admittance of materials.

Each LCZ is individually named and ordered by one or more distinguishing surface properties, which in most cases is the height/packing of roughness objects or the dominant land cover. The physical properties of all zones are measurable and nonspecific as to place or time (Table 7.1). The landscape universe consists of seventeen standard LCZs (Fig. 7.2) of which fifteen are defined by surface structure and cover and two by construction materials and anthropogenic heat emissions. The standard set is divided into 'built types' 1–10, and 'land-cover types' A–G (Table 7.1). Built types are composed of constructed features on a predominant land cover, which is paved for compact zones and low plants/scattered trees for open zones. Land-cover types can be classified into seasonal or ephemeral properties (i.e. bare trees, snow-covered ground, dry/wet ground) (Stewart and Oke, 2012).

7.1.3 *Local climate zone validation*

Stewart *et al.* (2014) present the first evaluation of LCZ with temperature observations and simulation results from surface-atmosphere models. They compare the effects of urban form, rural soil wetness, tree density, snow cover and human activity on LCZ temperatures from field sites in Nagano, Japan; Vancouver, Canada; and Uppsala, Sweden, thus representing cities of different cultural, historical, climatic and geographic settings.

The results (Table 7.2) show distinct thermal signatures of different zones, thus confirming quantitative support for the LCZ concept. They also justify the definition of heat island magnitude as an LCZ temperature difference, which facilitates communication and intercity comparison of results. This in turn is deemed to help heat island

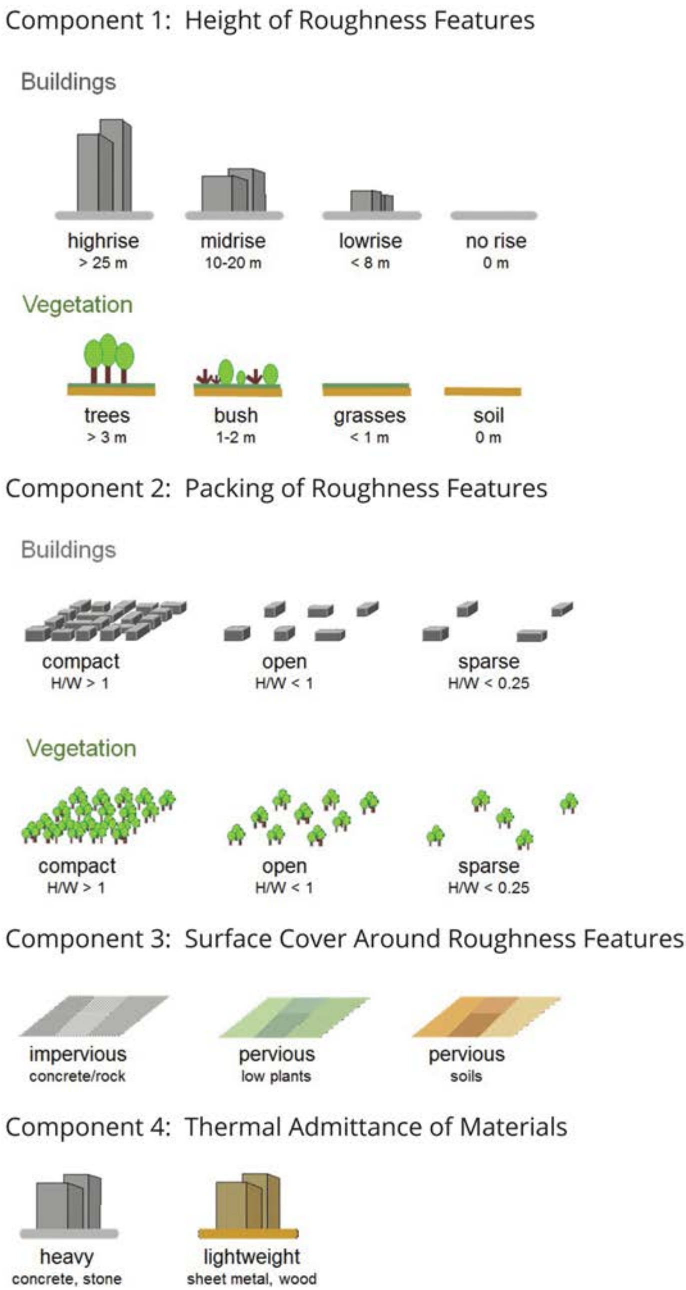


Figure 7.1. Factors in constructing LCZ framework. (Source: Stewart, 2011c. Used with permission)

Table 7.1. Values of geometric, surface cover, thermal, radiative, and metabolic properties for LCZ. (Source: Stewart and Oke, 2012. © American Meteorological Society. Used with permission)

Local climate zone (LCZ)	Sky view factor[a] (SVF)	Aspect ratio[b]	Building surface fraction[c] (BSF)	Impervious surface fraction[d] (ISF)	Pervious surface fraction[e] (PSF)	Height of roughness elements[f] (HRE)	Surface admittance[g]	Surface albedo[h]	Anthropogenic heat output[i]
LCZ 1	0.2–0.4	>2	40–60	40–60	<10	>25	1,500–1,800	0.10–0.20	50–300
LCZ 2	0.3–0.6	0.75–2.0	40–70	30–50	<20	10–25	1,500–2,200	0.10–0.20	<75
LCZ 3	0.2–0.6	0.75–1.5	40–70	20–50	<30	3–10	1,200–1,800	0.10–0.20	<50
LCZ 4	0.5–0.7	0.75–1.25	20–40	30–40	30–40	>25	1,400–1,800	0.12–0.25	<25
LCZ 5	0.5–0.8	0.3–0.75	20–40	30–50	20–40	10–25	1,400–2,000	0.12–0.25	<25
LCZ 6	0.6–0.9	0.3–0.75	20–40	20–50	30–60	3–10	1,200–1,800	0.12–0.25	<35
LCZ 7	0.2–0.5	1.0–2.0	60–90	<20	<30	2–4	800–1,500	0.15–0.35	<50
LCZ 8	>0.7	0.1–0.3	30–50	40–50	<20	3–10	1,200–1,800	0.15–0.25	<10
LCZ 9	>0.8	0.1–0.25	10–20	<20	60–80	3–10	1,000–1,800	0.12–0.25	>300
LCZ 10	0.6–0.9	0.2–0.5	20–30	20–40	40–50	5–15	1,000–2,500	0.12–0.20	0
LCZ A	<0.4	>1.0	<10	<10	>90	3–30	unknown	0.10–0.20	0
LCZ B	0.5–0.8	0.25–0.75	<10	<10	>90	3–15	1,000–1,800	0.15–0.25	0
LCZ C	0.7–0.9	0.25–1.0	<10	<10	>90	<2	700–1,500	0.15–0.30	0
LCZ D	>0.9	<0.1	<10	<10	>90	<1	1,200–1,600	0.15–0.25	0

LCZ E	>0.9	<0.1	<10	>90	<10	<0.25	1,200–2,500	0.15–0.30	0
LCZ F	>0.9	<0.1	<10	<10	>90	<0.25	600–1,400	0.20–0.35	0
LCZ G	>0.9	<0.1	<10	<10	>90	—	1,500	0.02–0.10	

Notes:

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 Ability of surface to accept or release heat ($J \cdot m^{-2} \cdot s^{-1/2} \cdot K^{-1}$). 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.

h Ratio of the amount of solar radiation reflected by a surface to the amount received by it. Varies with surface color, wetness, and roughness.

i Mean annual heat flux density ($W \cdot m^{-2}$) from fuel combustion and human activity (transportation, space cooling/heating, industrial processing, human metabolism). Varies significantly with latitude, season, and population density.

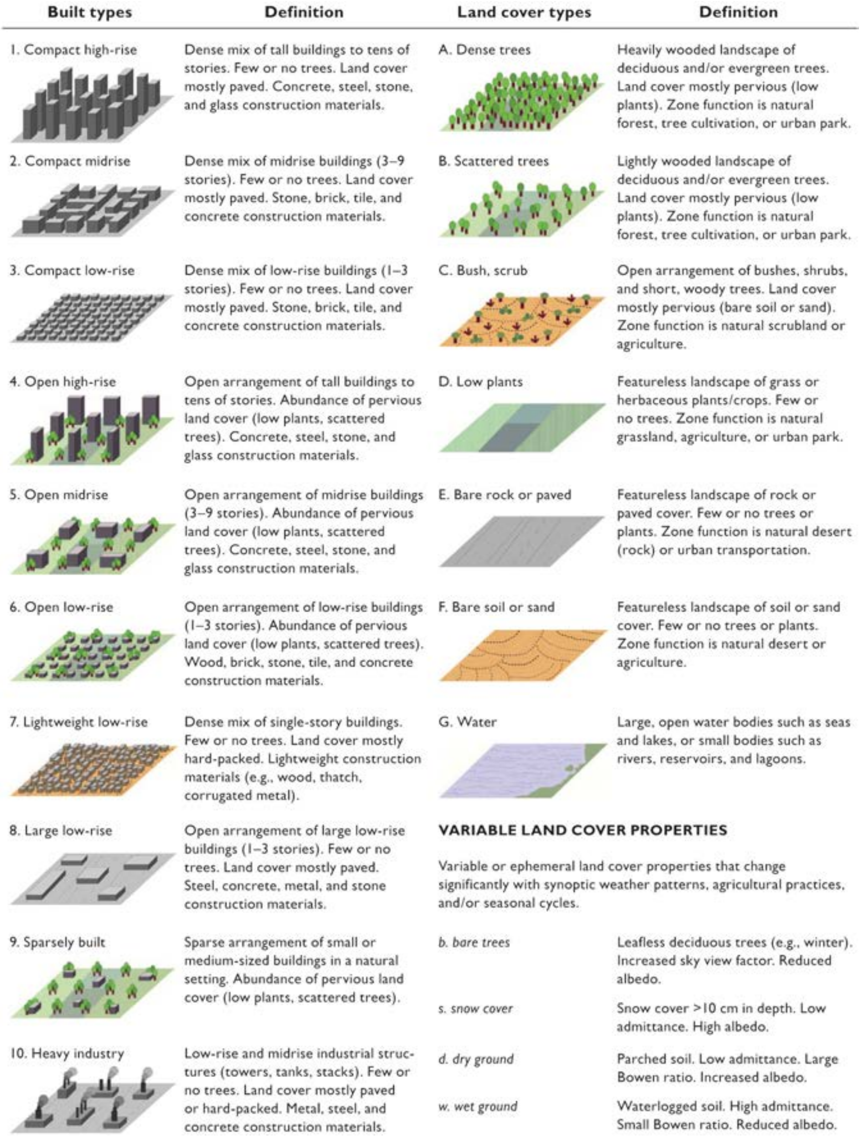


Figure 7.2. LCZ. (Source: Stewart and Oke, 2012. © American Meteorological Society. Used with permission)

Table 7.2. Comparison of modeled and observed diurnal temperature range (DTR) in selected locations and LCZ. (Source: Stewart *et al.*, 2014)

Local climate zone	DTR[a] modelled (K)	DTR[a] observed (K)	Location	Data Source
LCZ1: compact high-rise	6	5–8	Vancouver, Canada	McClean (1993)
		6–9	Tokyo, Japan	Japan Meteorological agency: http://data.jma.go.jp
LCZ2: compact mid-rise	6	8–10	Göteborg, Sweden	Eliasson, 1994
		11–15	Basel, Switzerland	Basel, Urban Boundary layer experiment (BUBBLE): http://www.geog.ubc.ca/~achrisin/researc/BUBBLE
LCZ3: compact low-rise	8	7–9	Kugahara, Japan	Kanda *et al.* 2005
LCZ5: open mid-rise	8	10–12	Göteborg, Sweden	Eliasson, 1994
		10–14	Uppsala, Sweden	
LCZ6: open low-rise	9	11–16	Uppsala, Sweden	
		12–15	Vancouver, Canada	Environmental Prediction in Canadian Cities (EPiCC) Network: http//www.epicc.ca
LCZ7: lightweight low-rise	11	10–14	São Paulo, Brazil	Silva and Ribeiro, 2006
LCZC: bush, scrub	20	17-23	Mohave, USA	Arizona Meteorological Network: http://ag.arizona.edu/azmet
LCZD: low plants	17	10–15	Vancouver, Canada	McClean (1993)
		15–18	Uppsala, Sweden	
LCZF: bare soil or sand	19	14–18	Basel, Switzerland	Basel, Urban Boundary layer experiment (BUBBLE): http://www.geog.ubc.ca/~achrisin/researc/BUBBLE

[a]DTRs are representative of summer and/or dry season days with light winds and clear or partly cloudy skies.

investigators to anticipate urban and rural thermal differences at the local scale, and to seek physical explanations for those differences. (Stewart *et al.*, 2014)

7.1.4 *Use of local climate zones*

The LCZ system remains relatively new, with its final iteration presented by Stewart *et al.* in 2012. Most of the work presented below is in mid-latitude cities. Work using the LCZ scheme in tropical contexts is seen in Hong Kong, India, Thailand and Sri Lanka.

A summary of the work and reviews are presented in the form of tables (Table 7.3 (tropical) and Table 7.4 (other)) highlighting the author, city and the parameters studied. It also attempts to present a brief insight into the objective and method of the studies. The literature cited is no means exhaustive; rather, it is an attempt to paint a picture of the wide-ranging application of the LCZ system.

As seen in Table 7.3, LCZ studies in the tropics done in Sri Lanka, India, Singapore, Thailand and Hong Kong highlight the heterogeneity of the built fabric and therefore the need for careful classification or the need for sub-classification.

The above evidence of usage suggests that LCZ has moved beyond its primary objective of a protocol for urban temperature studies, instead extending its scope to testing, mapping for development and urban planning/design strategies appropriate for LCZ-specific, neighborhood-level contexts. In this connection mention must be made of an exemplary approach adopted by the World Urban Database and Access Portal Tools (WUDAPT), where the primary objective is to "develop a database that uses consistent descriptors and gathers information at a suitable scale" (WUDAPT, 2014b).

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

Table 7.3. Previous work using LCZ classification as the primary tool — LCZ use in the tropics.

Author(s), year	City	Parameter(s) studied. Method used for LCZ classification	Remarks
Mapping and UHI Studies			
Villadiego and Velay-dabat, 2014	Barranquilla, Colombia	Thermal comfort, thermal sensation. Urban data from maps, plans, pictures and satellites images from Google Earth and Bing maps. Field studies to make observations and verify the information. The final map was designed using Quantum GIS software.	Different microclimate conditions were perceived between the zones, especially between Alto Prado (LCZ 6_4), the richest, and Cordialidad (LCZ 7B), the poorest neighborhood. It was considered that demo-spatial dynamics and urban planning in Barranquilla encourage inequalities in terms of climate conditions and thermal comfort.
Perera *et al.*, 2012	Colombo, Sri Lanka	UHI. Uses observational and site surveys to map urban blocks into LCZs. Applied surface heat island model to compare local warming effects of each LCZ.	Highlights the need for sub-classification.
Perera *et al.*, 2013	Colombo, Sri Lanka	UHI. Uses the results of the 2012 paper highlighted above.	Explored the effect of a LCZ change, and therefore UHI intensity, due to future development plans for the city.
Perera and Samanthi-laka, 2014	Colombo, Sri Lanka	UHI. In depth metadata study of selected urban blocks (based on the findings of Perera *et al.*, 2012).	The most predominant LCZs in Colombo were analyzed for their materiality effects on UHI. Surface temperature and typical façade materials formed the primary focus.

(*Continued*)

Table 7.3. (*Continued*)

Author(s), year	City	Parameter(s) studied. Method used for LCZ classification	Remarks
Siting of Weather Stations			
Siu and Hart, 2013	Hong Kong, china	LCZ for classification of weather-station siting.	Modified nomenclature and building height definition to conform to the high density settings of Hong Kong.
Wong, 2014	Hong Kong, China	LCZ for classification of weather-station siting. Remote sensing and GIS.	By employing the geographic information system (GIS) and global positioning system (GPS) software, the sampled data were mapped against urban structures and land uses to investigate the urban microclimate and the role of various environmental factors at the sampling locations.
Peng and Jim, 2013	Hong Kong, China	LCZ for classification of weather-station siting. ENVI-met. Green roofs on UHI.	Uses the Hong Kong urban form yardstick for residential buildings. Low-rise refers to 6 storeys or fewer, middle-rise 6–12 storeys, and high-rise *¿12* storeys. See (Siu and Hart, 2013).
(Thomas *et al.*, 2014)	Kochi, India	UHI. Mobile traverse. Physical measurements and Google images.	Thermal gradient between different zones and cooling rates observed in these zones were computed, which was deemed to validate the LCZ classification. Standard zone properties alone were found inadequate to explain variation of UHI intensity of same classes with different surface area and diverse adjacent zones.

			Two more zone properties — radial distance to adjacent zone, called zone boundary distance, and the nearest adjacent zone — were proposed to overcome inadequacies.
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. LCZs were assigned to the city of Mendoza using land use and land-cover (LULC) maps	
	Colombo, Sri Lanka	MRT. In depth metadata study of a selected urban block (based on the findings of Perera *et al.*, 2012).	Used the ranges defined in the LCZ system to explore the effect of varying surface cover characteristics in a typical urban block.
Perera and Weerasekara, 2014	Colombo, Sri Lanka	MRT. Outdoor thermal comfort. Based on the findings of Perera *et al.* (2012) as database for a urban canyon survey	Used a LCZ mapping of Colombo to survey and then identify the most frequent urban canyons formed by two adjacent LCZs. Then simulated using ENVI-met to ascertain the effect of the morphology change.

Table 7.4. Previous work using LCZ classification as the primary tool — LCZ use in other contexts.

Author(s), year	City	Parameter(s) studied. Method used for LCZ classification	Remarks
LCZ validation			
Coseo and Larsen, 2014	Chicago, IL	Used LCZ urban variable measures to match eight Chicago neighborhoods to LCZ classes.	A bivariate relationship analysis between variables and UHI intensity showed pervious surface fraction, impervious surface fraction and building surface fraction as significant.
Mapping and UHI Studies			
Middel*et al.*, 2012	Phoenix, AZ	Daytime cooling efficiency and diurnal energy balance. ENVI-met. Surface cover characteristics extended as a crucial element in the categorization. See also Middel *et al.* (2014).	LCZ used to define representative sample sites for evaluation of the spatial distribution of cooling efficiency indices in the study area.
Middel *et al.*, 2014	Phoenix, AZ	Urban form, landscaping and air temperature.	Sub-categorization of LCZ using custom land-cover characteristics. A departure from the definition of the land-cover LCZs to better represent the contextual uniqueness. See detailed discussion in Sec 7.1.5.4.

Emmanuel and Loconsole, 2015	Glasgow, Scotland	Mapping, ENVI-met, air temperature, surface temperature, thermal comfort. Green infrastructure for overheating adaptation. Ordnance survey and LIDAR (light detection and ranging) data to estimate building cover and building height/land cover or land use in the GCV (Glasgow Clyde Valley) region to estimate surface characteristics, together with ground truth verification of selected 'hot spots' using Google Earth and/or field visit to estimate building height and other physical parameters of selected areas.	Concluded that an increase in green infrastructure as a positive effect in mitigating urban overheating in a warmed future scenario, a reduction in the UHI effect, reductions in surface temperature and increased user thermal acceptability.
Bechtel *et al.*, 2012	Hamburg, Germany	UHI. Remote sensed classification. GIS.	Redefined LCZ categorizations to adhere to historical city contexts. See Sec. 7.1.5.4.
Acero *et al.*, 2014	Multiple cities	Mapping/comparative database for climate change impacts.	

(*Continued*)

Table 7.4. (*Continued*)

Author(s), year	City	Parameter(s) studied. Method used for LCZ classification	Remarks
Unger *et al.*, 2014	Szeged, Hungary	Mapping. GIS. The determination of the building block footprints and lot area polygons is based on the 3D building database of Szeged in ESRI shape-file format. All of the calculations were carried out with self-developed Fortran algorithms and for the visualization of the outputs Quantum GIS was used.	
Alexander and Mills, 2014	Dublin, Ireland	*In situ* stations and mobile traverses. Land-cover/land use maps as basis.	A 1 km^2 grid was coded with a LULC category and a number was randomly selected for examination to provide a link to LCZ type. Google Earth (GE) and Bing Maps (BM) were used to translate each selected grid cell LULC into a corresponding LCZ class using the LCZ datasheets.
Siting of Weather Stations			
Grimmond, 2013	London, UK		LCZ for classification of weather station siting.
Leconte *et al.*, 2014	Nancy, France	UHI. Mobile measurement method. LCZ for siting measurement points.	Explores the relationship between urban indicators and air temperature features, and the air temperature differences between LCZ types were analyzed.

Historical/Comparative Studies			
Hebbert, 2014			A historical perspective on similar systems.
Thermal Comfort/Climate Change/Vulnerability Impact Studies			
	Budapest, Hungary	Thermal comfort, PET, UTC.	LCZ classification for measurement site definition and comparison.
Müller *et al.*, 2013	Oberhausen, Germany	Climate change adaptation, PET, ENVI-met.	LCZ classification for measurement site definition and comparison.
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).	Based on the assumption that specific hazard (extreme climatic impact) severity and the population susceptibility are related with certain LCZ. Redefined LCZ categorizations to adhere to historical city contexts. See Sec. 7.1.5.4.

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 WUDAPT process, which 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.

7.1.5 *Mapping the local climate zones*

The process defined and developed by Stewart over the years is approached as a three-step progression. Stewart (2011b), defines the steps as:

1. define the area of influence;
2. collect site metadata;
3. select LCZ.

He also goes on to further elaborate on the third step, where subclassification of LCZs was explored. However, in Stewart and Oke's later work (Stewart and Oke, 2012) the process is slightly modified; the first two steps are interchanged. They define the process as:

1. collect site metadata;
2. define the thermal source area;
3. select the LCZ.

They recommend that the steps be applied in similar manner whether it is for a multi-year study or one that is more short-term. Due consideration of seasonal or ephemeral properties pertaining to soil moisture, snow cover and tree-leaf cover need to be adhered to.

7.1.5.1 *Step 1: collect site metadata*

Metadata refers to the state of the urban context around a particular measurement site. The recording of the surroundings of a measurement site ensures the consideration of the effect of 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).

Oke (2004) emphasizes the need to adequately describe the properties of urban districts that affect the atmosphere. He states "the most important features are the urban structure (dimensions of the buildings and the spaces between them, the street widths and street spacing), the urban cover (built-up, paved, vegetated, bare soil, water), the urban fabric (construction and natural materials) and the urban metabolism (heat, water and pollutants due to human activity)" (Oke, 2004). A detailed breakdown of the descriptors — all measureable and not specific to a particular date or time — is shown in Table 7.1.

Metadata collection has been the emphasis of many studies that have adopted the LCZ classification protocol, especially for mapping the existing urban fabric, providing further evidence to show that LCZ use has moved beyond urban temperature studies as originally intended and into other climate-related and urban design realms. The methods used vary from remote-sensed (Bechtel *et al.*, 2012; 2015; Unger *et al.*, 2014; Savić *et al.*, 2014; Emmanuel and Loconsole, 2015) to site-based surveys (Middel *et al.*, 2014; Perera *et al.*, 2012; Thomas *et al.*, 2014; Peng and Jim, 2013). The importance of 'ground truth' (Emmanuel and Loconsole, 2015) verification is emphasized. The heterogeneity of the urban fabric for different regions of the world and the attempt to classify them into the defined LCZ have posed a problem for researchers.

Bechtel (2012) states "the typology seems optimised for American morphologies and besides a few case studies for other areas (e.g. Stewart and Oke (2009) for Japan) it might have to be adapted or differentiated. European cities for instance contain much larger historic areas and hence a broad variety of compact morphologies" (Bechtel *et al.*, 2012). The importance of local expertise in LCZ classification is stressed.

Similarly, Peng and Jim (2013) modified LCZ parameters using the Hong Kong urban-form yardstick for residential buildings (low-rise fewer than 6 storeys; mid-rise 6–12 storeys; and high-rise more than 12 storeys).

The question that arises from such decisions is the effect on communication and comparison of the site with those of other studies. This factor is discussed in more detail in Step 3a — create sub-classes for LCZs.

7.1.5.2 *Step 2: define the thermal source area*

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.

The thermal source area for a temperature measurement is the total surface area 'seen' by the sensor (sometimes called its 'footprint' or 'circle of influence'). In other words, it is the surface area from which the temperature signal is derived and subsequently is carried, via turbulent transport, to the sensor (Oke, 2004). The source area of standard contact thermometers extends upwind for meters to kilometers depending on instrument height, surface geometry, and boundary layer wind and stability conditions (Kljun *et al.*, 2002).

The size, shape, and orientation of turbulent source areas evolve with time (Fig. 7.3). Over periods of, say, an hour, the area is elliptical and oriented in the upwind direction of the sensor (Schmid, 2002). Because of temporal changes in stability, and especially wind direction, the ellipses are centred upon, but oscillate around, the

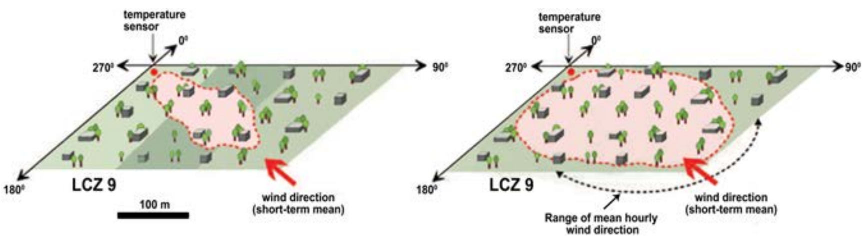


Figure 7.3. Hypothetical source areas and surface wind directions for a screen-height temperature sensor in prevailing southeast winds; (left) short-term (<1 h) source area; (right) mean daily source area. (Source: Stewart and Oke, 2012. © American Meteorological Society. Used with permission)

measurement site so that, over time, they form a misshapen circle. The dimensions of the source area should be computed, ideally with a footprint model (e.g. Kljun *et al.*, 2002; Schmid, 2002). The approximate size and orientation of the area can otherwise be estimated from (a) the vectors of a wind rose for that location and time period, and (b) an empirically based 'rule of thumb' that states that the source area for a screen-height temperature sensor in a neutrally stable atmosphere extends, on average, no more than a few hundred meters away (Tanner, 1963; Mizuno *et al.*, 1990/1991; Runnalls and Oke, 2006).

Estimating the source area for a screen-height thermometer in an urban area is a challenging task that has hardly been scientifically investigated. It can be anticipated that screen-height temperature measurements in a canopy layer with compact buildings have smaller and more poorly defined source areas than those of open urban and rural zones. The sources will include upwind buildings, the walls and floor of an upwind street, and perhaps a branching network of more distant street canyons that channel surface air toward the measurement site.

Stewart and Oke (2012) further suggest that each LCZ should have a minimum diameter of 400–1000 m (i.e. a radius of 200–500 m) so that the adjusted portion of its internal boundary layer lies entirely within the zone and does not overlap with surrounding LCZs of different structure or cover. A review of recent literature pertaining to studies using the LCZ system and quoted by Stewart and Oke (2012) reveals varying definition of the 'thermal source area' or 'area of influence' (Table 7.5).

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. If the

Table 7.5. Approaches to source area definition.

Author(s)	Year	Source area size[a]	Limitations
Tanner	1963	A few hundred meters.	The approximate size on average in a neutrally stable atmosphere extends.
Mizuno *et al.*	1990/91	Suggesting a radius of 100–200 m.	The circle of influence is difficult to quantify, but relatively uniform in surface cover, geometry, and human activity.
Kljun *et al.*	2002	Meters to kilometers.	Depending on instrument height, surface geometry, and boundary layer wind and stability conditions.
Runnalls and Oke	2006	A radius of about 0.5 km typically.	Depending on the building density and boundary conditions, but for the distance influencing a screen-level (1.5 m) temperature or humidity sensor when it is stable conditions.
Stewart *et al.*	2012	Not more than a few hundred meters away (a radius of 200–500 m).	Estimating the source area for a screen-height thermometer in an urban area is a challenging task that has hardly been scientifically investigated. The sources will include upwind buildings, the walls and floor of an upwind street, and perhaps a branching network of more distant street canyons that channel surface air toward the measurement site.

Emmanuel and Loconsole	2013	500 × 500 m area surrounding each measurement site.	For calculation of built fractions and green cover; 1 km diameter circles were considered.
Bechtel *et al.*	2012, 2015	A 100 m grid resolution was chosen.	
Thomas *et al.*	2014	100 × 100 m for a 2 km radius around fixed measurement sites and 500 × 500 m grid for other areas.	Explores the effect of adjacent LCZ.
Perera *et al.*	2012	A typical urban block as the primary element.	Explores the classified urban morphology as the climatic context for urban thermal comfort studies.
Srivanit	2013	All weather stations are defined by a circle of influence whose radius extends 500 m.	Recommended by Oke (2004) on the Initial Guidance to Obtain Representative Meteorological Observations at Urban Sites by World Meteorological Organization.

[a] The approximate size is varies with latitude (geographic location), climate region, topography and season.

location of the sensor cannot be moved, temperature data retrieved from that site should be stratified first according to wind direction, then to LCZ (Stewart and Oke, 2012).

7.1.5.3 *Step 3: select the local climate zone*

Classification or selection of LCZs is driven by the metadata collected in Step 1. The primary objective is to ascertain the best fit between the properties defined in the LCZs and those collected at field sites.

If a situation arises where the measured or estimated values align poorly with those of the LCZs, the selection of matching LCZs becomes one of interpolation rather than finding an exact fit. The set of parameters that takes precedence in this regard is the surface cover fractions (especially building cover), and therefore should be employed to guide the process. Surface cover fractions strongly influence local thermal climate and are easily estimated from land-cover maps, aerial photographs, and Google Earth images (Stewart, 2011b).

In a situation where matching and interpolation fails to define the collected metadata, two alternatives are presented:

- highlight in detail where the metadata differs from the nearest equivalent LCZ class; or
- create sub-classes (sub-classify) to represent combinations of built types, land-cover types, and land-cover properties.

The guidelines are broadly categorized according to the following (see Fig. 7.4 as an example).

- 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 UHI phenomenon.

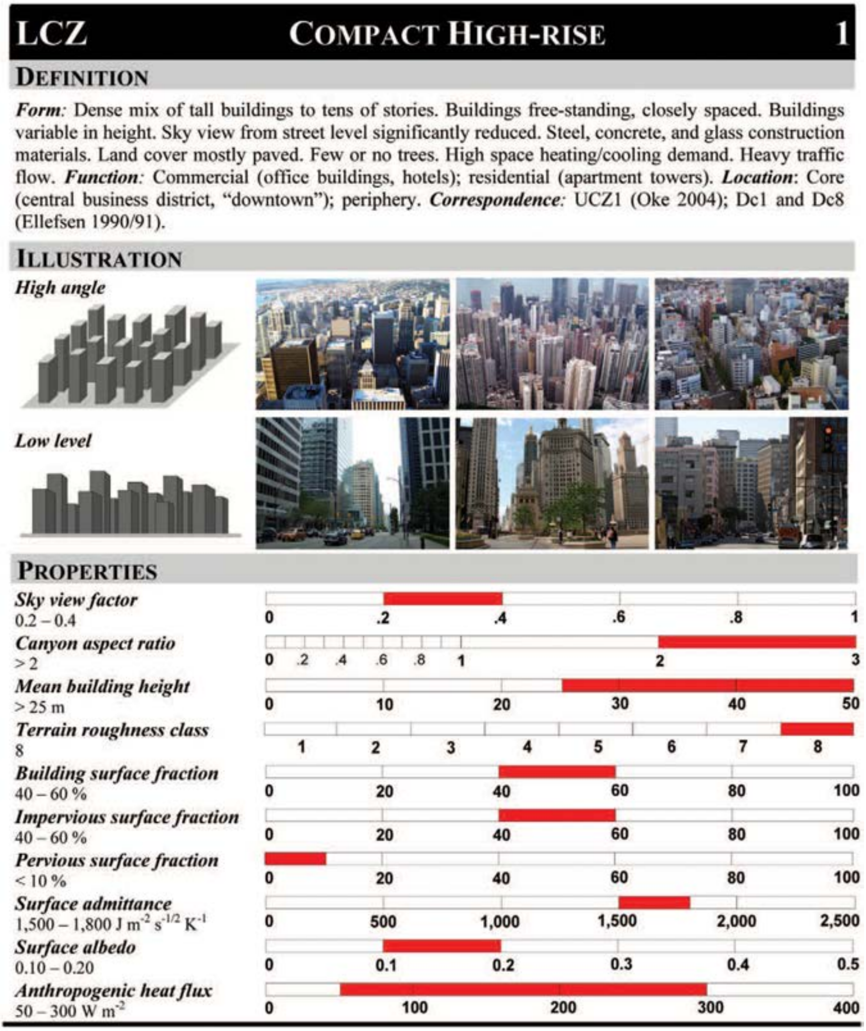


Figure 7.4. LCZ datasheet for selection (LCZ 1 as example). (Source: Stewart and Oke, 2012. © American Meteorological Society. Used with permission)

7.1.5.4 *Step 3a: define sub-classes*

New sub-classes can be created to represent a better fit in areas that do not adhere to the main LCZs. The sub-classes combine built types, land-cover types, and land-cover properties to communicate

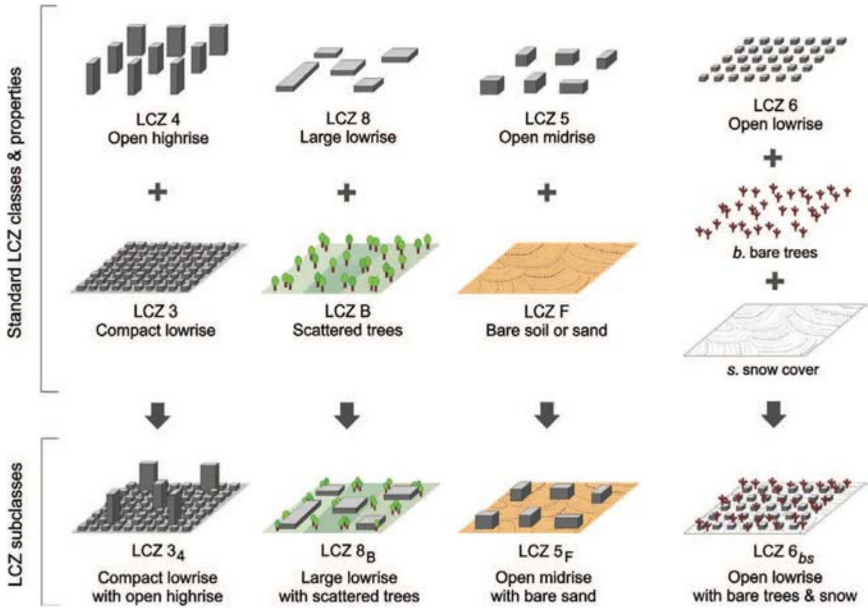


Figure 7.5. An outline view of the selection and definition of LCZ sub-classes. (Source: Stewart and Oke, 2012. © American Meteorological Society. Used with permission)

the mixing of the LCZs. As shown in Fig. 7.5, a primary LCZ type is qualified by the use of a secondary LCZ.

Stewart *et al.* (2012) define the process in detail as follows:

> The notation for new sub-classes is LCZ X_{ai}, where X is the higher parent class in the standard set of LCZs, 'a' is the lower parent class (if applicable) from the standard set, and 'i' is a variable or ephemeral land-cover property (if applicable). Land-cover properties are selected from the subset of bare trees (b), snow cover (s), dry ground (d), and wet ground (w) (Table 7.2). Identifiers 'a' and 'i' may each be assigned one or more classes or properties. For example, a site whose building geometry is open mid-rise (LCZ 5) but whose surface cover is pre-dominantly bush, scrub (LCZ C) should be notated as LCZ 5_C to represent the main features of its two parent classes, the first in a higher position of the LCZ order (baseline character 5) and the second in a lower position (subscript C).
>
> All standard LCZ classes with extensive pervious cover (A–D, F, 4–6, and 9) are prescribed an intermediate soil moisture status, meaning that soil water content is below field capacity but above wilting point. In

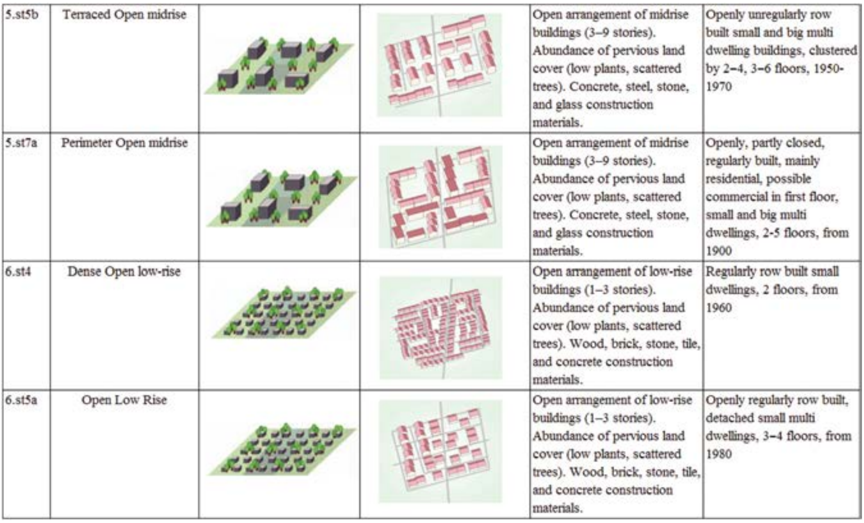
> this state, soil moisture is available to plants and the soil feels pliable and slightly sticky. If soils are saturated (i.e. water content is above field capacity, and water is easily squeezed from the soil), the site should be sub-classified as 'wet' (with subscript w). Soils submerged in shallow water due to natural drainage or flood irrigation (e.g. wetlands, paddy fields, detention storage ponds) are also considered wet. If soils are parched (i.e. water content is below wilting point), soil moisture is unavailable to plants and the soil feels loose, powdery, or hard-crusted. The site in this case should be sub-classified as 'dry' (subscript d). Finally, if a site is covered with $> 10\,\mathrm{cm}$ of snow, it should be sub-classified as 'snow cover' (subscript s). (Stewart and Oke, 2012)

Bechtel *et al.* (2015) in their approach to mapping LCZs for a worldwide database of the form and function of cities, state

Some restrictions emerge from the origin of the LCZ scheme for characterizing screen-height air temperature observations. Identifying an ideal spot to place instruments in order to measure a representative local climate signal implies concentration on prototypes for a specific local climate (which means homogenous structures within a turbulent footprint) rather than mixed, indistinct or doubtful candidates. On the other hand, when discretizing an entire city, each class will unavoidably have a certain amount of internal heterogeneity, since it is composed of a variety of urban landscapes that are part of a continuum rather than discrete types. This means that for classification purposes, the class boundaries, rather than centroids, become crucial, demanding a precise formulation of the boundaries between the classes. These considerations can be summarized in the following questions: Can an LCZ be assigned to any urban structure? Additionally, can only one LCZ be assigned to a given structure? Likewise, it can be asked, whether the classes are complete, comprehensive, and disjoint? (Bechtel *et al.*, 2015)

The scheme addresses these problems with the possibility to define sub-classes, which are essentially mixtures between the standard classes. (Bechtel *et al.*, 2015)

Although examples of sub-classes are presented, the adopted processes do not always adhere to those presented in Stewart's classification protocol. It is understood that these approaches were generated due to very specific circumstances and difficulties in applying the LCZ system in a given local context.



5.st5b	Terraced 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.	Openly unregularly row built small and big multi dwelling buildings, clustered by 2–4, 3–6 floors, 1950-1970
5.st7a	Perimeter 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.	Openly, partly closed, regularly built, mainly residential, possible commercial in first floor, small and big multi dwellings, 2-5 floors, from 1900
6.st4	Dense 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.	Regularly row built small dwellings, 2 floors, from 1960
6.st5a	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.	Openly regularly row built, detached small multi dwellings, 3–4 floors, from 1980

Figure 7.6. LCZ classes to match morphological structures from the German energetic district planning. (Source: Kaveckis and Bechtel, 2014. Used with permission)

Bechtel *et al.* (2012, 2015) enhance/redefine LCZ classes to match morphological structures from the German energetic district planning (Fig. 7.6). They state "Now each class contains more detailed morphological, use and cover description. This helps us to differentiate LCZ into sub-classes with different properties and more accurately identify impacts of hazards" (Kaveckis and Bechtel, 2014).

Similarly, Siu and Hart (2013), classifying measurement sites in Hong Kong, re-interpreted the LCZ classifications to fit existing sites (see also Peng and Jim (2013), discussed in Sec. 7.1.5.1, above). They also modified the nomenclature used in their communication of zones (classified according to building (B) and natural (N) series). Middel *et al.* (2014) explored urban form by classifying according to building types and then applying native landscape scenarios. The integration of the landscape as a sub-classification varies from what is defined in the LCZ system.

Although sub-classes add flexibility to the LCZ system, we give several caveats for their use. First, the system as proposed does not provide surface property values for sub-classes, and thus their thermal climates may not be known *a priori*. At best, one can estimate the surface property values — and surface air temperatures — by weighting the known values of two (or more) standard classes. Second, the thermal climate of an LCZ sub-class is not expected to differ significantly from either of its two (or more) parent classes, because maximum thermal contrasts between successive zones in the standard set are typically no more than 1–2 K (Stewart and Oke, 2010). Third, the purpose of LCZs is to ease the process of site classification and metadata reporting for heat island investigators. Creating too many, or too complex, sub-classes undermines this principal function. While sub-classes may enhance the physical description of a site, they may not improve communication or comparison of that site with other studies. Sub-classes are justified when they describe sites whose secondary features are thought to affect the local climate, or whose features may otherwise relate to the particular aims of a climate investigation (Stewart and Oke, 2012).

7.2 Mapping LCZ in the Tropics — Case Study of Colombo, Sri Lanka

We now present an example of LCZ application in a warm humid climate setting (Colombo, Sri Lanka). It draws upon studies by Perera *et al.* (2012, 2013).

The first study mapped the LCZs and related warming in Colombo, Sri Lanka (Perera *et al.*, 2012). In a follow-up to this study by the same authors in 2013, the projected changes in urban morphology of the city in relation to its future development plans and its effect on the UHI intensity were explored and this is discussed in detail in Sec. 7.3.

Colombo, Sri Lanka (6°54′ N, 79° 52′ E) (Köppen–Geiger classification Af — tropical rainforest Climate), is the largest city in the country and its former administrative capital and is situated on the western coast of the island. It has a typical warm, humid coastal climate affected by the UHI phenomenon. 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.

Colombo is predominantly residential: Colombo Municipality area has over 42% residential land use, with 3.5% commercial and 4.5% business (JICA, 2014) (Fig. 7.7). This results in low building density in many areas of the city except in the central business district of Fort and Pettah. The Indian Ocean on the western edge creates 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.

7.2.1 *Local climate zone classification*

7.2.1.1 *Steps 1 and 2: Collect site metadata and thermal source area*

The approach here is to understand the city in terms of morphology and its influence on the local climate. Therefore, the selection of an 'area of influence' — as defined by Stewart (2011b) — adopts urban blocks as the primary defining element for the study.

The selection of an urban block as a defined element allows effective simulation of future climate in subsequent research. The urban block offers a definite boundary, be it a street, green area or water body. Factors encompassing plot coverage, built area fraction and green area ratio are better defined in a situation where the building plot boundaries and area are well established. The objective is also to relate to zoning and building regulations that are primarily based on plot and zone structure.

The main source for information was 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. 7.8). The verification and modification of the block boundaries was done using on-field surveys and Google Earth imagery. The urban are in the range of 100 × 200 m at the minimum (along the coast abutting two major vehicular arteries).

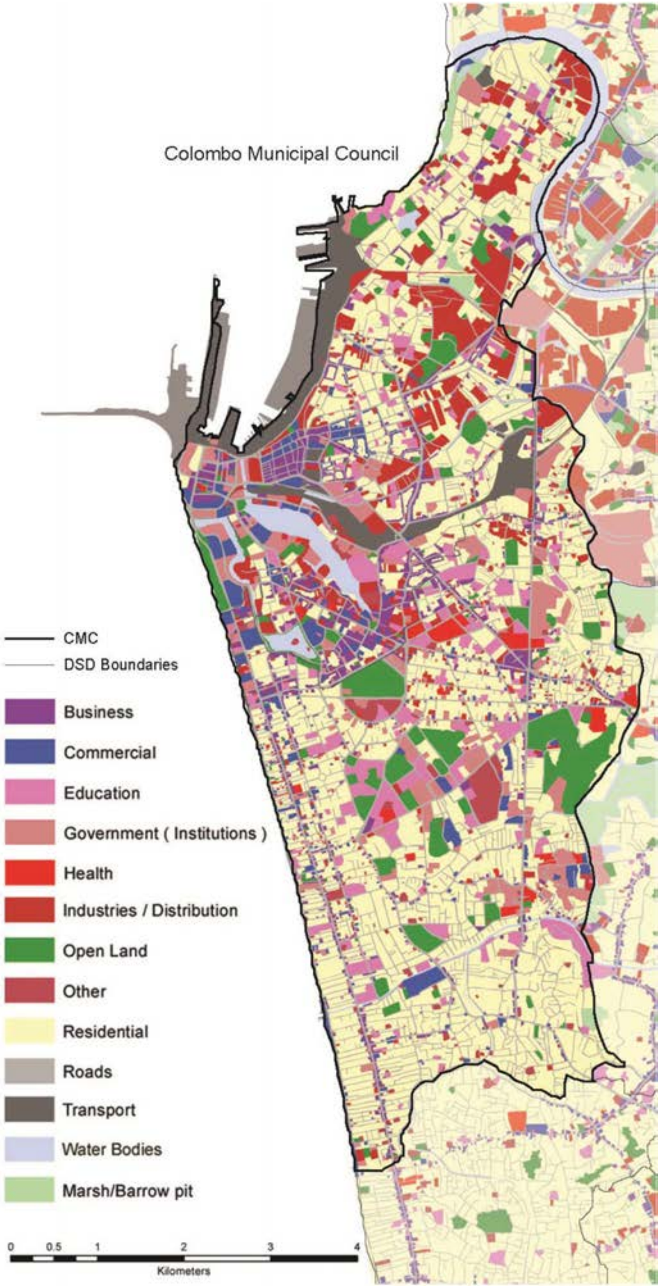


Figure 7.7. Colombo Municipal Council (CMC) land use in 2013. (Source: Japan International Coorporation Agency, 2014. Used with permission)

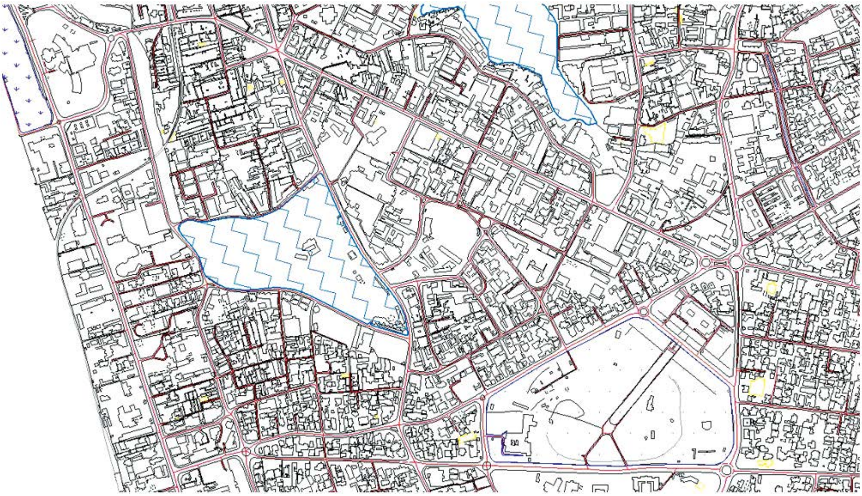


Figure 7.8. Detailed map of Colombo (representative sample area). (Source: Perera, 2015)

The data collected adhered to the 'zone properties' defined in the LCZ data sheets developed by Stewart (2011) (see Fig 7.4). The adopted method is given in detail in Table 7.6.

Each urban block was mapped individually, matching similar and adjacent blocks in situations where similarities were obvious. In-depth knowledge of the context and the availability of an accurate digital (AutoCAD) drawing of the context hastened the process.

7.2.1.2 *Step 3: select the local climate zone*

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) (see Fig. 7.4).

While Colombo is dominated by low-rise residential and mixed-use zones, these urban blocks are seeing an infusion of mid-rise and high-rise blocks. Most of the city is classified as LCZ3 (48.1%), LCZ2 (8.9%) and LCZ8 (23.7%). LCZ1 (0.3%) and LCZ4 (1%) form a very small fraction of Colombo's built fabric. A significant percentage falls under the category of LCZ7 (4.9%) (Figs. 7.9 and 7.10 and Table 7.7).

Table 7.6. Urban block metadata 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 (z_0) for city and country landscapes	As per LCZ data sheets
Surface admittance	Ability of surface to accept or release heat ($J{\cdot}m^{-2}{\cdot}s^{-1/2}{\cdot}K^{-1}$). 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

(*Continued*)

Table 7.6. (*Continued*)

Property	Definition	Method adopted
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 ($W{\cdot}m^{-2}$) 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

Figure 7.11 shows typical views of the predominant LCZ classes/sub-classes in Colombo.

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.

7.2.1.3 *Step 3a: define sub-classes*

The sub-classification of LCZ types where the packing of roughness elements are defined as 'compact' (example LCZs 1–3) sees a sub-classification with LCZs of mainly the 'built series' (example LCZ3_7, LCZ2_4), while the 'open' LCZ series (LCZs 4–6 and LCZ8) is sub-classified with LCZs of the 'land-cover series' (Example LCZ8_B, LCZ6_D). This is most evident in LCZ8, where the nature of the open ground is significant. (see Fig. 7.10 and Table 7.7)

LCZ3 with sub-classification LCZ7 is noteworthy; where these areas would have been previously categorized as 'lightweight low-rise'

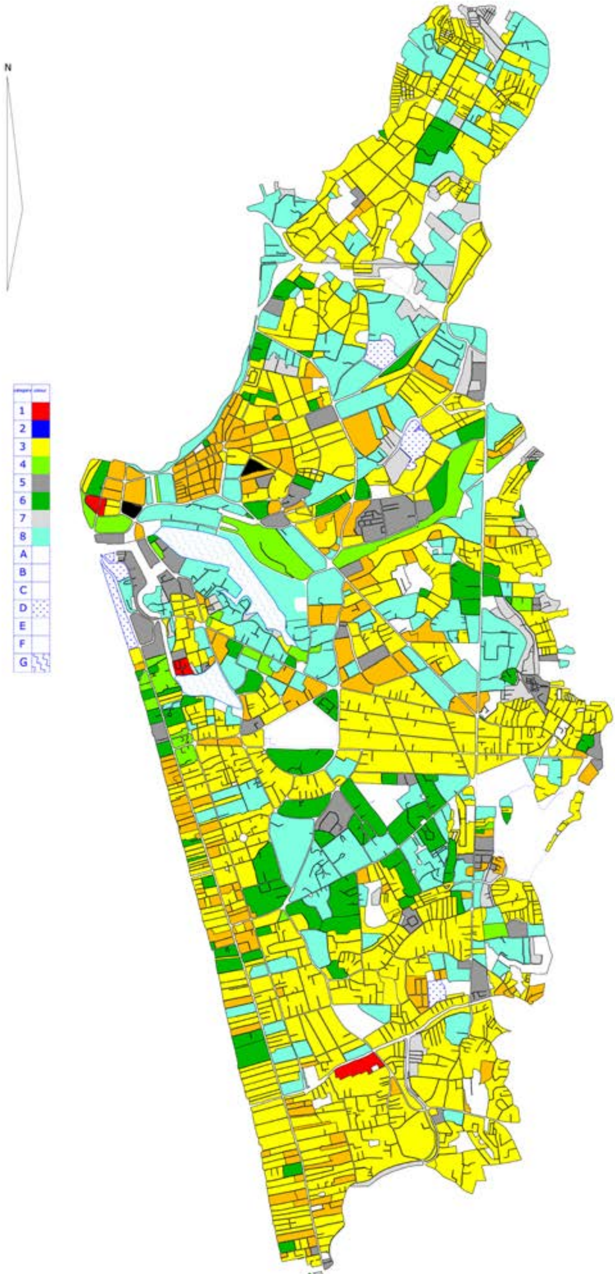


Figure 7.9. LCZ classes for Colombo. (Source: Perera *et al.*, 2012)

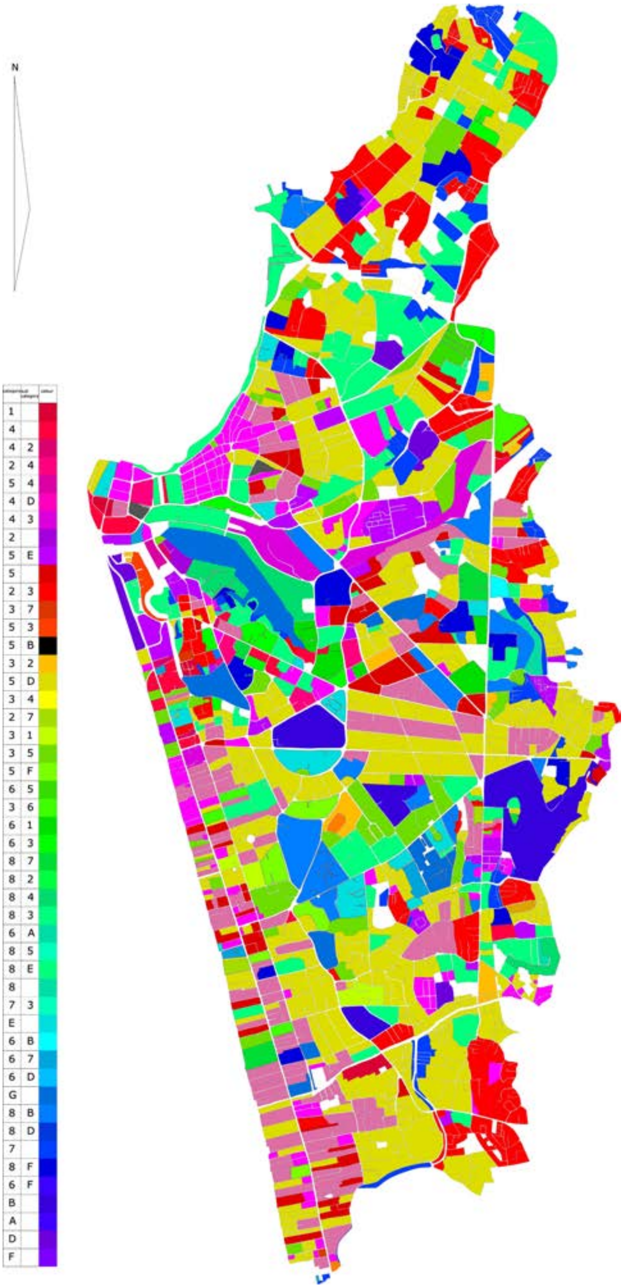


Figure 7.10. LCZ sub-classes for Colombo. (Source: Perera *et al.*, 2012)

Table 7.7. LCZ and sub-classification patterns for Colombo. (Source: Perera *et al.* 2013)

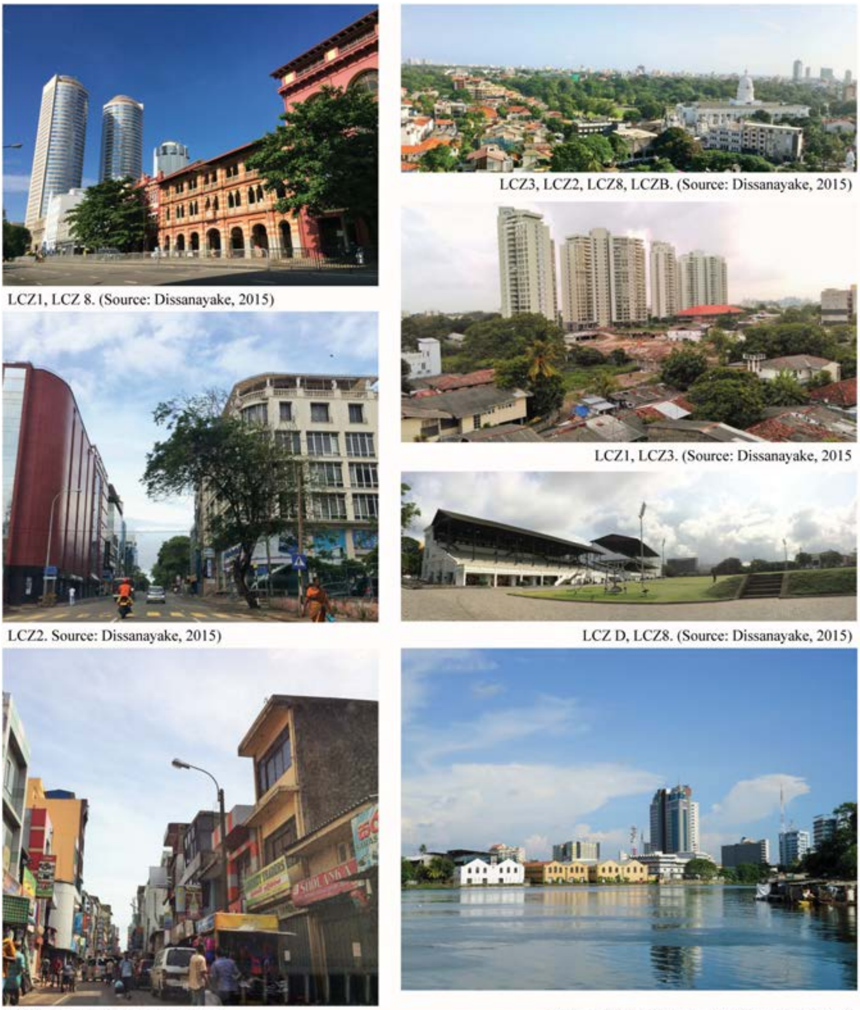
Local Climate Zone		**Sub-Classification Category**														
Zone Number	Zone Title	1	2	3	4	5	6	7	8	A	B	C	D	E	F	G
1	compact high-rise	■														
2	compact mid-rise		■	■	■			■								
3	compact low-rise		■	■	■	■	■	■								
4	open high-rise		■	■	■								■			
5	open mid-rise			■	■	■					■		■	■	■	
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															■

or ‘slum’ areas in the city, they have now developed with more permanent materials. The development has not changed its plot structure; thus they maintain a high aspect ratio.

7.2.2 *Estimating the local warming effects of the urban fabric*

Colombo is fast-changing in terms of land-use patterns and building morphology. This is reflected in the zoning plans for the city, developed by the Urban Development Authority, the statutory agency responsible for managing urban growth, which had been amended several times in recent years. The current approach to zoning plans moves away from a morphology option (maximum-permissible-height-based strategy) to a density approach (floor area ratio (FAR)-based strategy).

Given this change in the urban development approach, we wished to explore the local warming consequences of the proposed urban fabric (Perera *et al.*, 2012, 2013). For this purpose, the city was first classified into LCZs (both the existing as well as the proposed morphology) and a 1D surface heat island model (SHIM) developed by Johnson *et al.* (1991) was utilized to simulate the likely local warming



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.

Figure 7.11. Typical LCZs of Colombo. (All images used with permission)

effects of the urban fabric changes (as captured by the LCZ classification).

SHIM is a simple force-restore model that simulates the nocturnal cooling of an urban canyon (walls and street) under the 'ideal' conditions of calm winds and clear skies. Turbulence and advection are not incorporated. It is assumed that all cooling takes place due to radiative heat loss; no account of evaporative heat transfer is possible. However, our purpose was to explore the warming effects of changes to the urban fabric (geometry); thus, 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 epitomized by densely arranged buildings with excessive thermal capacities.

The numerical model was run for a stable, dry day (04 January 2011). The SHIM 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 (7° 10′ N; 79° 52′ E; elevation 8 m asl; WMO Station ID: 434500) and an 'urban' weather station at the Colombo City Airport (6° 49′ N; 79° 52′ E; elevation 5 m asl; WMO Station ID: 434670).

The results of the estimates of likely local warming are shown in Table 7.8 (refer to Fig. 7.3 for LCZ nomenclature). The shaded diagonal depicts LCZs that are not sub-categorized. Rows depict the primary LCZ categorization while columns show the sub-categorization LCZs. Temperature values are depicted as UHI intensity (i.e. the difference between the LCZ and a control 'rural' LCZ).

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. 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. The lowest intensity is seen in the land-cover-type LCZs. The land-cover series (A through G) incorporated in the sub-categorization of built series types — LCZ8 (large low-rise) and LCZ6 (open low-rise) — are very significant. LCZ8 areas form a large part of the city, mainly along the city's canal system.

The areas with the highest built area fraction, LCZ7 (lightweight low-rise) areas, are affected significantly by the material properties modeled (thermal admittance and emissivity). Significant areas of

Table 7.8. Likely local warming due to urban fabric changes in Colombo. (Source: Perera *et al.*, 2012)

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

the city have previously seen 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).

In summary, we can state that:

- UHI intensities in Colombo range from 0.09°C to 4.40°C.
- LCZ classification shows the existence of a significant mix in the city's urban fabric. Although large areas of Colombo remain low-rise, several of these blocks are seeing an infusion of mid-rise and high-rise blocks, which is shown to lead to greater UHI intensity.
- Ground cover and materiality aspects of the urban fabric can greatly affect the local warming intensity.

7.2.3 *Likely local warming effect in the future*

Applying the same method to the proposed development plan for Colombo in 2020 shows significant increases in UHI intensity (Table 7.9). This assumes the development plan for 2020 has taken full effect and the urban fabric developed to its maximum allowable levels. UHI intensities are shown over and above the existing LCZ for a particular urban block.

Table 7.9. Projected temperature difference above existing LCZ. (Source: Perera *et al.*, 2013)

Existing LCZ		Projected LCZ							
Zone number	Zone Title	1	2	3	4	5	6	7	8
1	compact high-rise								
2	compact mid-rise	0.44			0.39				
3	compact low-rise	1.21	0.77		1.16				
4	open high-rise	0.05							
5	open mid-rise	0.69	0.25						
6	open low-rise	2.53	2.09	1.32	2.48	1.84			−0.77
7	lightweight low-rise	4.09	3.65	2.88	4.04	3.4	1.56		0.79
8	large low-rise	3.3	2.86	2.09	3.25	2.61	0.77		

The following conclusions could be reached:

- Overall, the LCZ changes in almost all urban blocks have a negative impact on the UHI intensity.
- The greatest difference (4.09°C) is seen when LCZ7 (lightweight low-rise) is transformed in to LCZ1 (compact high-rise areas). This process has already started at a fast rate in Colombo, where under-served communities are now being housed in high-rise developments. Although the strategy allows the release of otherwise underutilized land for development, this could have a 'climatic penalty'.
- A similar penalty applies to warehouse areas (LCZ8) 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 intensity. The LCZ change that would create a reduction in the UHI intensity is when LCZ6 areas are transformed in to LCZ8 (a reduction of 0.77°C). This is currently seen in Colombo, where traditional residential areas are being transformed into mainly educational institutions, while maintaining the open spaces and low building heights.
- 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 since almost all transformations to higher densities have negative impacts.

Thus, the proposed development plan has both positive and negative impacts. The positive impacts occur when the already densely built areas are earmarked for more intense development, leading to minimal changes in UHI intensity (a range of 0.44–1.21°C for the transformed LCZ2 and LCZ3 areas in Table 7.9). Similarly, the preservation of LCZ5 and LCZ6 areas is also a positive. The negative impacts include the development of under-served areas (LCZ7) into high-rise areas, creating the largest UHI intensity change of 4.09°C (LCZ1) and 4.04°C (LCZ4).

One way to avoid such negative consequences is to limit the change of LCZ7 into open low-rise (LCZ6: 1.56°C change) or large low-rise (LCZ8: 0.79°C change). Examples of such changes may include the creation of educational or similar institutional functions, high-end housing areas, mixed developments with large green spaces and reduced vehicular traffic.

Thus, the 'slum clearance' approach currently undertaken could aim to free valuable land for development but the people so removed could be re-housed in the more dense parts of the city. Apart from the social benefits, such a strategy would at least maintain the current UHI intensities without making them worse (Perera *et al.*, 2013).

7.3 LCZ and Context-Specific Planning/Design Guidelines

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 (Perera, 2015).

LCZ classes could form the basis of urban zones (as opposed to the current practice of either land-use or urban activities). An advantage of such an approach is that critically stressed areas (i.e. urban 'hot spots') could be easily identified. For example, areas identified as LCZ1 could be expected to be hotter, given the presence of high-rise 'walls' and concentrations of anthropogenic heat in limited areas of the city. An LCZ-based zoning approach would also highlight areas that need preservation. Examples could include zones such as LCZ2, LCZ3 and LCZ8, further development of which would increase their heat island magnitude. It would also highlight areas that could be further developed and/or re-categorized without a severe climatic penalty. For example, zones classified as LCZ8 could be repurposed without changing much of the morphology of the city fabric (Perera *et al.*, 2013).

This raises the question as to how urban planners and designers could incorporate social and economic needs and priorities of a city. Fortuitously, an LCZ-based zoning approach meshes well with climate sensitivity requirements. The LCZ system indirectly incorporates land use and activity patterns via its consideration of anthropogenic heat, which is a proxy variable of socioeconomic factors. And, the estimation of likely future changes to a given LCZ zone also has socioeconomic factors built into it.

Furthermore an LCZ-based zoning approach provides sufficient flexibility (see for example, the ranges shown in Table 7.1). The possibility to sub-classify the zones extends the flexibility. The sub-categorization and within-zone definition of properties allow sufficient heterogeneity and design flexibility to the fabric. Thus, they also maintain the socioeconomic effectiveness in a sustainable urban system. The 'shadow umbrella' approach (Emmanuel, 2005) is a good example of this built-in flexibility, where the block shape is consciously modified to maximize the climatic potential of the outdoors by manipulating individual building blocks. It also considers functional use categorization as well.

Having thus defined the urban zones, an LCZ-based approach could also be used to specify building-level regulations. These could include the specification of minimum plot size, minimum width between building lines of a public or private street/road, maximum permissible FAR, maximum plot coverage, open space around the building, etc. It could further provide the basis for monitoring local development at block-level, by defining permissible maximum sky view factor (SVF), FAR, height of roughness elements (HRE), and built surface fraction (BSF) to control/establish block maximum as per LCZ, rather than a city-wide blanket regulations. Additionally, zone-level definitions of pervious surface fraction (PSF), impervious surface fraction (ISF) and green surface fraction (GSF) could provide local flexibility at the level of individual building plots.

7.4 LCZ and the Tropics — Final Word

The advantage of an LCZ-based zoning approach is that "classes are local in scale, climatic in nature, and zonal in its representation" (Stewart and Oke, 2012). It provides the protocol for rapid mapping, yet is comparable across similar urban contexts. The benefit of such a system for data-scarce developing cities is immense. However some caveats are in order.

7.4.1 *Simplification and attendant ills*

City-scale microclimatic measurement regimes or simulation models are resource intensive. On-site measurements cannot dispel the influence of anthropogenic and material aspects; neither can they look ahead to a globally warmed scenario. While an LCZ-based planning approach provides a quick and cost-effective start, the danger is in the over-simplification of the context, especially in using them as planning zones. It should be kept in mind that the LCZ system was originally developed 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 and Oke, 2012).

7.4.2 *Limitations in zone-specific future planning strategies*

LCZ classification incorporates geometric and surface characteristics together with thermal, radiative and metabolic value ranges in their selection. The adoption of such LCZ-based zoning has the advantage of implementing city-scale interventions that not only have characteristic morphology, but also the incorporation of climate characteristics within the selection. It also gives insight into the probable anthropogenic impact of a zone in an existing climatic context as well as for a projected future climate change scenario. While all these aspects are positive and especially useful in resource-poor developing cities, a key limitation is that the simplification limits the ability to specify zone-specific future planning strategies. Given that the zones are so demarcated as to highlight climatic peculiarities within cities, the necessary simplification of the system limits its ability to devise distinct guidelines for each zone.

7.4.3 *Interpretation issues*

While the LCZ parameter ranges provide a useful basis for zone-specific guidelines, there is considerable room for interpretation, which could lead to difficulties in implementation. For example, in the context of Colombo, Sri Lanka, establishing zone-specific density and building regulations could be open to disagreement. Additional contestation could occur where sub-categorization is allowed (i.e. where and to what extent?). How will the values change? There may be further issues related to equity (who gets to exceed the zone norms and how are these defined?).

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 and Oke, 2012). It is now time that context-specific knowledge from several tropical cities are applied to both the classification and the creation of sub-classes so as to enhance its usefulness to this data-poor but rapidly changing region.

References

Acero, J. *et al.* (2014). *Physical and cost typology for buildings and infrastructure/project database*, European Union's Seventh Programme for Research, Technological Development and Demonstration. RAMSES — Reconciling Adaptation, Mitigation and Sustainable Development for Cities. Grant Agreement No. 308497. Available at www.ramses-cities.eu/resources/

Aguilar, E., Auer, I., Brunet, M., Peterson, T. C., Wieringa, J. (2003). Guidance on metadata and homogenization. WMO Tech. Doc. 1186, 53 pp.

Alcoforado, M.-J., Andrade, H., Lopes, A., Vasconcelos, J., 2009. Application of climatic guidelines to urban planning: the example of Lisbon (Portugal). *Landscape and Urban Planning* **90**(1–2), 56–65.

Alexander, P. and Mills, G. (2014). Local climate classification and Dublin's urban heat island, *Atmosphere*, **5**(4), 755–774. Available at http://www.mdpi.com/2073-4433/5/4/755/.

Auer, A.H. (1978) Correlation of land use and cover with meteorological anomalies. *J. Appl. Meteor.*, **17**, 636–643.

Bechtel, B. *et al.* (2012). "Classification of Local Climate Zones from multitemporal remote sensing data", proceedings of ICUC8 — 8th International Conference on Urban Climates, 6–10 August 2012, Dublin, Ireland.

Bechtel, B. *et al.* (2015). Mapping local climate zones for a worldwide database of the form and function of cities, *ISPRS International Journal of Geo-Information*, **4**(1), 199–219. Available at http://www.mdpi.com/2220-9964/4/1/199/.

Chandler, T.J. (1965). The Climate of London. Hutchinson, 292 pp.

Chen, L. and Ng, E. (2011). Quantitative urban climate mapping based on a geographical database: a simulation approach using Hong Kong as a case study, *International Journal of Applied Earth Observation and Geoinformation*, **13**(4), 586–594. Available at http://dx.doi.org/10.1016/j.jag.2011.03.003.

Coseo, P. and Larsen, L. (2014). "How Local Climate Zones Predict Urban Heat Islands in Eight Chicago Neighborhoods", proceedings of The Association of Collegiate Schools of Planning Conference, 30 October–2 November 2014, Philadelphia, PA.

Dubois, C. *et al.* (2012). "Adapting cities to climate change?: heat and urban form", proceedings of ICUC8 — 8th International Conference on Urban Climates, 6–10 August 2012, Dublin, Ireland.

Ellefsen, R., (1990/91). Mapping and measuring buildings in the urban canopy boundary layer in ten US cities. *Energ. Buildings*, **15–16**, 1025–1049.

Emmanuel, R. (2005). *An Urban Approach to Climate-sensitive Design: Strategies for the Tropics, First Ed.*., Spon Press, London, UK.

Emmanuel, R. and Loconsole, A. (2015). Green infrastructure as an adaptation approach to tackle urban overheating in the Glasgow Clyde Valley Region, *Landscape & Urban Planning*, **138**, 71–86.

Emmanuel, R., Perera, N.G.R. and Mahuwanthi, H. (2011). Mitigating urban warming as an adaptation strategy to climate change in the warm, humid tropics (in review).

Grimmond, S. (2013). Observing London: weather data needed for London to thrive. London Climate Change Partnership. Available at http://climatelondon.org.uk/wp-content/uploads/2013/07/Observing-London-Final.pdf.

Hebbert, M. (2014). Climatology for city planning in historical perspective, *Urban Climate*, **10**, 204–215.

Japan International Coorporation Agency (2014). *Urban Transport System Development Project, Colombo*. Available at http://www.transport.gov.lk/web/images/stories/F-CoMTrans_Main_S.pdf.

Johnson, G.T., Oke, T.R., Lyons, T.J., Steyn, D.G., Watson, I.D., Voogt, J.A. (1991). *Simulation of surface urban heat islands under "ideal" conditions at night. Part 1: theory and tests against field data. Boundary Layer Meteorol.* 56, pp. 275–294.

Kaveckis, G. and Bechtel, B. (2014). "Land Use Based Urban Vulnerability to Climate Change Assessment", proceedings of The 9th International Conference "Environmental Engineering", 22–23 May 2014, Vilnius, Lithuania. Available at: http://enviro.vgtu.lt.

Kljun, N., Rotach, M., Schmid, H.P. (2002). A three-dimensional backward Lagrangian footprint model for a wide range of boundary-layer stratifications. *Bound.-Layer Meteor.*, **103**, 205–226.

Leconte, F. *et al.* (2014). Using local climate zone scheme for UHI assessment: Evaluation of the method using mobile measurements, *Building and Environment*, **83**, 39–49.

Middel, A. *et al.* (2012). Daytime cooling efficiency and diurnal energy balance in Phoenix, Arizona, USA, *Climate Research*, **54**(1), 21–34.

Middel, A. *et al.* (2014). Impact of urban form and design on mid-afternoon microclimate in Phoenix Local Climate Zones, *Landscape and Urban Planning*, **122**, 16–28.

Mizuno, M., Nakamura, Y., Murakami, H., Yamamoto, S., (1990/91). Effects of land use on urban horizontal atmospheric temperature distributions. *Energ. Buildings*, **15**, 165–176.

Müller, N., Kuttler, W. and Barlag, A.-B. (2013). Counteracting urban climate change: adaptation measures and their effect on thermal comfort, *Theoretical and Applied Climatology*, **115**(1–2), 243–257. Available at http://link.springer.com/10.1007/s00704-013-0890-4.

Oke, T.R. (2004). Siting and Exposure of Meteorological Instruments at Urban Sites. Proceedings of 27th NATO/CCMS International Technical Meeting on Air Pollution Modelling and its Application, Banff, Canada. 25–29 October.

Peng, L.L.H. and Jim, C.Y. (2013). Green-roof effects on neighborhood microclimate and human thermal sensation, *Energies*, **6**, 598–618.

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.

Perera, N.G.R., Emmanuel, M.P.R. and Mahanama, P.K.S. (2013). "Projected urban development , changing "Local Climate Zones" and relative warming effects in Colombo, Sri Lanka", proceedings of International Conference on Cities, People and Places, 15–16 October 2013, Colombo, Sri Lanka.

Perera, N.G.R. and Samanthilaka, K.P.P.R. (2014). "Effect of Street Canyon Materials on the Urban Heat Island Phenomenon in Colombo", proceedings of International Conference on Cities, People and Places, 15–16 October 2013, Colombo, Sri Lanka.

Perera, N.G.R. (2015). Climate-Sensitive Urban Public Space: A Sustainable Approach in a Sri Lankan Context, Unpublished PhD Thesis, University of Moratuwa, Sri Lanka.

Runnalls, K.E., Oke, T.R. (2006). A technique to detect microclimate inhomogeneities in historical records of screen-level air temperature. *J. Climate*, **19**, 959–978.

Savić, S. *et al.* (2014). "Mapping of Local Climate Zones in two neighboring Central-European cities located in similar geographical environments" proceedings of the International Geographical Union — Regional Conference, 18–22 August 2014, Kraków, Poland. Available at http://urban-path.hu/~dragan/Conferencepresentation-Krakow,2014.pdf.

Schmid, H.P. (2002). Footprint modeling for vegetation atmosphere exchange studies: A review and perspective. *Agric. For. Meteor.*, **113**, 159–183.

Siu, L.W. and Hart, M.A. (2013). Quantifying urban heat island intensity in Hong Kong, *Environmental Monitoring and Assessment*, **185**, 4383–4398.

Srivanit, M. 2013. Integrated urban thermal environment assessemnt methods for multi-scale spatial planning, Unpublished PhD Thesis, Dept of Science and Advanced Technology, Graduate School of Science and Engineering, Saga University, Japan.

Stewart, I. and Oke, T. (2009). "Classifying Urban Climate Field Sites by "Local Climate Zones": The Case of Nagano, Japan", proceedings of the 7th International Conference on Urban Climate, 29 June–3 July 2009, Yokohama, Japan.

Stewart, I.D. (2011a). A systematic review and scientific critique of methodology in modern urban heat island literature, *International Journal of Climatology*, **31**(2), 200–217.

Stewart, I.D. (2011b). *Redefining the Urban Heat Island*, Unpublished PhD Thesis, The University of British Columbia, Vancouver, BC.

Stewart, I.D., (2011c). Local climate zones: Origins, development, and application to urban heat island studies. Paper presented at the Annual Meeting of the American Association of Geographers. Seattle, USA. April 12–16.

Stewart, I.D., Oke, T.R. (2012). Local climate zones for urban temperature studies. *Bull. Amer. Meteor. Soc.*, **93**, 1879–1900.

Stewart, I.D., Oke, T.R. and Krayenhoff, S. (2014). Evaluation of the "local climate zone" scheme using temperature observations and model simulations, *International Journal of Climatology*, **34**(4), 1062–1080.

Tanaka, T., Ogasawara, T., Koshi, H., Yoshida, S., Sadohara, S., Moriyama, M., (2009). Urban environmental climate maps for supporting urban-planning related work of local governments in Japan: case studies of Yokohama and Sakai. In: Paper presented at the 7th International Conference on Urban Climate (ICUC-7), Yokohama, Japan, 29 June–3 July.

Tanner, C.B. (1963). Basic Instrumentation and Measurements for Plant Environment and Micrometeorology. Vol. 6, Soils Bulletin, University of Wisconsin Soil Science Dept., 200 pp.

Thomas, G. *et al.* (2014). Analysis of Urban Heat Island in Kochi, India, Using a Modified Local Climate Zone Classification, *Procedia Environmental Sciences*, **21**, 3–13. Available at http://linkinghub.elsevier.com/retrieve/pii/S1878029614001340.

Unger, J., Lelovics, E. and Gál, T. (2014). Local climate zone mapping using GIS methods in Szeged, *Hungarian Geographical Bulletin*, **63**(1), 29–41.

Ustrnul, Z., Czekierda, D., (2005). Application of GIS for the development of climatological air temperature maps: an example from Poland. *Meteorological Applications*, **12**, 43–50.
VDI. (1997). VDI Guideline 3787, Part 1: Environmental Meteorology — Climate and Air Pollution Maps for Cities and Regions. The Association of German Engineers.
Villadiego, K. and Velay-dabat, M.A. (2014). Outdoor thermal comfort in a hot and humid climate of Colombia?: a field study in Barranquilla, *Building and Environment*, **75**, 142–152.
Wong, P.Y.P. (2014). *A GIS Approach to Analyzing Microclimate Variations and the Urban Heat Island Phenomenon in Hong Kong*, Unpublished PhD 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.

Chapter 8

Urban climate modeling: Challenges in the tropics

Renganathan Giridharan

8.1 Introduction

In the wake of explosive population growth coinciding with a warming climate, cities have tended to prioritize economic development over environmental issues (Giridharan, 2005; Adebayo, 1990–91). However, lack of consideration of environmental issues by planners and urban designers does not mean that they do not appreciate relevant issues; it is that they lack the necessary tools and expertise to assess complex environmental issues critically based on planning and urban design parameters (Ng, 2012; Giridharan, 2005). Most of the available tools are developed by climatologists who are more focused on atmospheric physics. Very often urban climatologists give the least importance to urban design variables in their modeling approaches; as a result, urban designers tend to assess the climate parameters subjectively (Ali-Toudert and Mayer, 2006; Giridharan *et al.*, 2007; Ooka, 2007). Model developers need to understand the importance of urban design in improving urban climate and develop models incorporating all critical urban design variables at a very fine spatial scale (Emmanuel *et al.*, 2007). This could be achieved by urban designers with backgrounds in climatology developing models or modifying relevant climate models such that the outcome or the finding of the models could be applied constructively to urban design or physical planning (Golany, 1996; Ooka, 2007). Such models will have huge potential in tropical cities since most such conurbations are in the process of development.

The modification of urban climate primarily results in changes in outdoor air quality and temperature (Hidalgo *et al.*, 2008, Santamouris, 2001, Oke, 1987; Roth, 2007). The air quality issues on most occasions are a regional phenomenon, i.e. the primary factors are not in the micro-environment. However, air circulation has an impact on the aging of the air, i.e. how long a particular poor-quality air remains in the atmosphere. This air circulation is modified by morphology (Oke, 1987) and therefore relating urban variations to air quality is a very complex task; changes could take place in a few seconds on one occasion while it could be a few days or seasonal on another. Meanwhile, microclimate studies have established that changes in outdoor temperature are often largely a local occurrence, especially in high-density areas (Giridharan *et al.*, 2007, Yang *et al.*, 2011). These changes in outdoor temperatures are identified largely in the form of urban heat-island intensity (UHI) (Oke, 1987; Santamouris, 2001; Roth, 2007). Therefore, urban climate studies generally use the UHI or changes in outdoor temperatures as a yardstick to assess the environment (Santamouris, 2001; Giridharan *et al.*, 2007; Emmanuel, 2005; Yang *et al.*, 2011). This chapter will briefly outline the energy and mass exchange and discuss issues related to assessing outdoor temperature using urban climate models while focusing on tropical climate and urban morphology.

8.2 Energy and Mass Exchange in Urban Areas

Urban climate studies in the context of architecture and urban design are more concerned with changes taking place within the urban canopy layer (UCL). The UCL is the layer between the land surface and the roof of buildings, i.e. a layer beneath roof-level (Fig. 8.1) and atmospheric changes in this layer are produced at a microscale (0.01–1000 m). The zone between the top of the UCL and unaltered regional wind is known as the urban boundary layer (UBL). Although the characteristics of the UCL and the UBL are different, periodic atmospheric changes in UCL are controlled by the UBL. This is largely

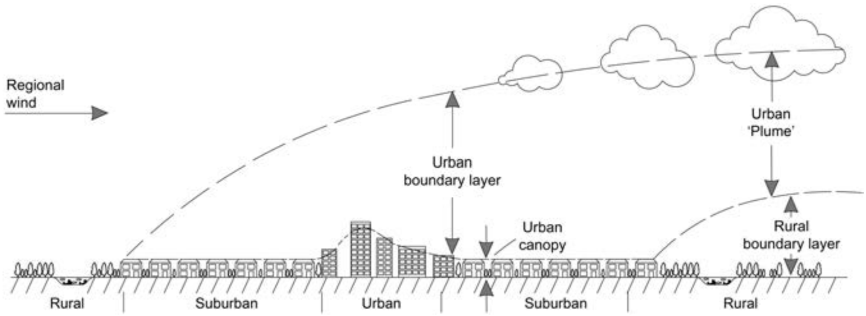


Figure 8.1. Conceptual sketch showing the canopy and boundary layer. (Source: Author)

due to the periodic mixing of air taking place in the UBL. This mixing zone is called the wake layer, which is crucial for the UBL and UCL energy budget and is very much context-dependent (geographical factors) (Oke, 1987). The area from the ground to the top of the UBL is called the planetary boundary layer (PBL). The changes in UBL and PBL are generally studied at the mesoscale.

Within the UCL, the balance of surface energy along with wind provides the driving force for vertical fluxes of heat, mass and momentum (Oke, 1988). The primary source of surface energy is solar radiation, i.e. short-wave radiation coming from sun. A portion of short-wave radiation that falls on a surface is being absorbed while the rest is being reflected. The reflected component is a function of surface albedo. A surface with an albedo value of 1 reflects 100% of the radiation while a surface with 0 albedo absorbs 100%; that is, a higher albedo surface reflects more short-wave radiation. However, in urban areas, the *urban* albedo determines the reflectivity (Fig. 8.2). In other words, surface albedo is the reflective property of individual material while urban albedo is the reflectivity of the urban mosaics, i.e. multiple surfaces (Aida, 1982). The characteristics of this mosaic are determined by urban geometry (Oke, 1988; Shashua-Bar and Hoffman, 2003).

In a city, a street flanked by buildings on either side is called an urban canyon. This canyon is defined by aspect ratio, i.e. the average height of buildings on either side of the street divided by the

Figure 8.2. Urban mosaic undergoing multiple reflection. (Source: Author)

street width. The aspect ratio and street orientation with respect to the sun have a significant impact on the timing and magnitude of energy flow within the canopy layer (Ali-Toudert and Mayer, 2006). For example, in a north-south street orientation, the annual radiation exchange in a high aspect ratio location is different from that of a low aspect ratio. Furthermore, a high aspect ratio and north-south orientated street in a temperate climate will have a different level of annual radiation exchange compared to one in a tropical climate (Oke, 1987; 1988). Unlike in a temperate climate, solar altitude in a tropical climate does not dramatically change from season to season.

The absorption of short-wave radiation by a surface is a function of absorptivity and exposure to solar radiation. The absorbed short-wave radiation raises the temperature of the surface and this, in turn, results in the emission of long-wave radiation with the degree of long-wave emission depending on the emissivity of the surface. A surface with 100% emissivity will emit all the absorbed radiation while a zero emissivity surface will not emit any radiation. The portion of the emitted long-wave radiation is lost into a clear sky while the remainder undergoes multiple reflections within the urban canyon. For example, construction materials such as asphalt, concrete and roofing tiles have very high heat capacity compared to forest cover and natural features. Therefore, they have the capacity to absorb and store large amounts of thermal energy (i.e. both short- and long-wave radiation). When the environment cools they emit the stored energy back into the environment in the form of long-wave radiation. According to Arnfield (1982), canyon geometry increases the urban emissivity of individual urban materials. This increase in emissivity leads to the emission of more long-wave radiation. However, weathering and pollution within the canyon could potentially reduce emissivity. Even if urban emissivity is slightly less than rural, it will have a greater impact on UHI since the extent of urban surfaces is much greater.

In the UCL, there could be a surplus of short- and long-wave radiation. In the canyon, this surplus of long-wave radiation is a function of surface temperature, emissivity, the portion of visible sky (sky view) and turbidity. At the same time, surplus of short-wave radiation is a function of sky view and turbidity. During the day, a substantial part of the surplus energy is utilized by vegetation (Huang *et al.*, 1987; Hidalgo *et al.*, 2008; Shashua-Bar *et al.*, 2006). The surplus short-wave radiation is utilized for photosynthesis and evapotranspiration while long-wave is utilized solely for evapotranspiration. The photosynthesis process helps to reduce the outdoor temperature due to the absorption of sunlight (short-wave radiation). Radiation falling on the surface of vegetation heats the leaves, resulting in water evaporation from soil as plants extract water through the roots and then evaporate it through their leaves. When there is a lack of vegetation but a presence of urban pollution, this surplus energy reaches the surface materials and air. This will result in high air temperatures during the day and the enhancement of heat storage in the surface. This stored heat is released into urban air after sunset, reducing the night's cooling capacity. Further, a low sky view and the presence of pollution reduce the cooling capacity of vertical urban surfaces (Fig. 8.3). As a result, this heat is also trapped in the urban canyon, resulting in higher nighttime temperatures.

Another type of heat that contributes to changes in urban canopy layer temperature is anthropogenic heat. Anthropogenic heat is released during the operation of systems that support human activities, such as transport, air conditioning and cooking. Although

Figure 8.3. Narrow street and pollution due to anthropogenic heat and incompatible developments. (Source: Author)

research in the 1960s suggested that UHI was largely due to changes in radiation balance and not anthropogenic heat (Landsberg, 1981), it may not be the case in high-density, high-rise settings, especially at night (Oke, 1998; Santamouris, 2001; Giridharan *et al.*, 2007). Building variables such as percentage of glazing and elements such as shading devices have significant impacts on internal and external heat gain, and they directly affect anthropogenic heat by impacting cooling load (Watkins *et al.*, 2002; Givoni, 1998; Ali-Toudert and Mayer, 2007). Research conducted in Japan has shown that air conditioning systems (which throw out indoor heat into the canyon) are one of the main causes of high temperature levels inside high-rise high-density canyons (Ooka, 2007).

The radiation emitted to the sky will depend on turbidity, i.e. the cloudiness or haziness found in urban areas. The density of turbidity is a function of water vapor and particles in the atmosphere. Generally, air movement is very weak in tropical cities compared to those in temperate climates, resulting in a poor level of pollution dispersion (Oke *et al.*, 1990–91). When excessive heat interacts with this stagnated pollution, moisture-heavy products are formed, leading to hazy conditions. Furthermore, turbulence will determine the rate of dispersion. Generally, turbulence increases near a tall building, and on the leeward side of the same building (Gago *et al.*, 2013, Golany,

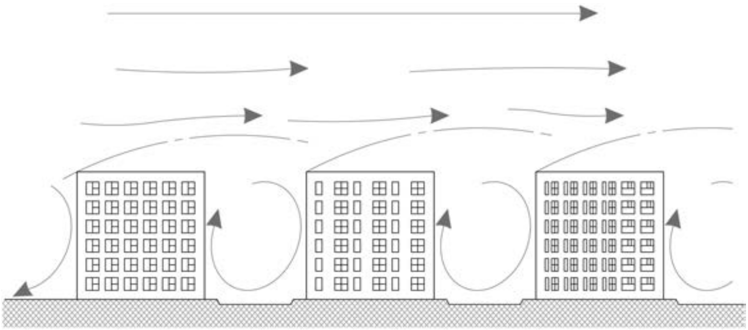


Figure 8.4. Conceptual sketch showing skimming effect. (Source: Author)

1996). On the other hand, where there is an array of buildings, even in the context of high-density and high aspect ratio, there is a transition to a skimming flow regime (Fig. 8.4), i.e. the bulk of the air does not enter the canyon (Santamouris, 2001; Oke, 1987). It should be noted that turbidity will also determine the intensity of incoming radiation and, fundamentally, the level of scattering of radiation in the atmosphere.

The above discussion on energy and mass exchange in urban environments revolves around surface energy balance, wind velocity and turbulence, anthropogenic heat exchange, soil and atmospheric moisture, and pollution levels. In essence, the urban features that modify the energy and mass exchange and thus contribute to environmental changes are (Hidalgo *et al.*, 2008):

- heterogeneity of the building (roughness elements) — turbulence regime;
- impervious surface materials and lack of vegetation-hydrological cycle and pollutant deposition;
- release of anthropogenic heat — thermal regime;
- release of pollutants — affects the transfer of radiation, cloud formation and precipitation; and
- the street geometry — wind flow regime and exchange of heat between different surfaces.

8.3 Tropical Climate and Characteristics of Urban Morphology

The tropical climate is generally considered to be hot and humid (Oke, 1987). According to Roth (2007), it is more appropriate, when studying tropical urban climate, to refer to sub-classifications created by Köppen in line with the geographical variation. These sub-classifications are wet climate (Singapore), wet/dry climate (Mumbai), monsoon climate (Jakarta) and highland climate (Mexico City). Such sub-classification is a good starting point to control and assess urban environments. Furthermore, this is a clear indication that moisture/water availability will be one of main determinants of tropical climate.

The tropical climate is not subject to major seasonal and diurnal variability like the temperate climate. However, it shows substantial variations in terms of space, especially due to characteristics of vegetation and solar altitude (Adebayo, 1990–91; Oke, 1987; Giridharan *et al.*, 2007; Chow and Roth, 2006; Yang *et al.*, 2010; Watkins *et al.*, 2002; Santamouris, 2001; Kolokotroni and Giridharan; 2008). As indicated before, unlike in temperate climates, solar altitude does not dramatically change in a tropical climate from season to season. Furthermore, for the critical part of the day, say 11 a.m.–3 p.m., the sun is positioned almost directly overhead.

Tropical vegetation is generally evergreen and dense while that of a temperate climate is both deciduous and evergreen. In a tropical climate, cool and warm conditions are purely a function of the level of precipitation and, especially, torrential rains could alter the urban climate over a substantial period. This period depends on the duration of rain and the amount of surface drainage (urban percolation). This is in contrast to a temperate climate's winter and summer, which are largely a function of intensity and duration of solar radiation.

In general, a hot-humid climate possesses the following characteristics (Givoni, 1998):

- general discomfort with high temperature and humidity;
- heavy torrential rain;
- enhancement of mould and fungi growth;

- rapid rusting of metals;
- rotting of wood and other organic material;
- rapid decay of building material; and
- prevalence of insects, flies and mosquitoes.

Urban morphology primarily covers features such as building form, skyline, plot size, land use, pattern of movement and street pattern. These factors interact with meteorological variables and modify the climate (Oke, 1987; Givoni, 1998; Santamouris, 2001). On most occasions urban morphology is classified based on a grouping of buildings and street (i.e. canyon) geometry. Canyon geometry is also called 'urban form', which, in turn, can be classified as compact, dispersed or clustered (Golany, 1996). The compact form and clustered form are suitable for hot-dry and cold-dry climates while the dispersed form is suitable for hot and humid climates (the tropics). Traditionally, tropical urban areas consist of linear built forms to enhance natural ventilation for cooling (Fig. 8.5). The buildings have high pitched roofs and high internal height to drain rain water and enhance air circulation. Paths and streets are shaded with most of the shading being in the form of vegetation. Urban layouts are based on low

Figure 8.5. Collage representing tropical urban characteristics. (Source: Author)

density and large inter-building spaces. In terms of urban setting, most of the tropical urban areas, especially the major cities, are close to seafronts and follow a linear development pattern parallel to the coastline. Outdoor temperature changes in these coastal urban areas are largely determined by convective activity, cloud, precipitation, and land and sea breeze (Sham, 1990–91; Giridharan *et al.*, 2007; Emmanuel and Johansson, 2006; Ng, 2012). In these cities the coastal fronts are generally cooler than rest of the city but the effect is limited to a thin zone (Tso, 1996). According to Evans and Schiller (1990–91), extending this zone to include a larger neighborhood depends on the openness of the first two avenues parallel to the seafront.

The pattern of air movement also depends on the characteristics of population density. In North America and Europe the correlation between changes in population and corresponding changes in temperature is very strong (Oke, 1987; Santamouris, 2001). However, in tropical cities the correlation between population and the UHI appears to be weak due to the influence of the topographical factors (Landsberg, 1981). However, in high-rise and high-density situations the influence of population appears to supersede that of topography and moves towards having a stronger relationship with changes in outdoor temperature (Giridharan, 2007; Park, 1987). Furthermore, a general premise is that for every 100 m rise in topography there is a temperature drop of 1°C. However, in the tropics, especially inland where urban areas incorporate large bodies of water and topographical changes, occasional temperature inversions are experienced. In this context, it is difficult to untangle the contribution of water body, topography and urbanization on changes in temperature. Generally, though, a high level of UHI occurs during anticyclonic conditions (Oke, 1987; Chow and Roth, 2006). However, a weak level of UHI could be observed during rainy, cloudy or windy seasons (Giridharan *et al.*, 2007; Li and Lam, 2001).

8.4 Modeling in the Context of Urban Design

Modeling a building's indoor environment is reasonably straightforward. A building's fabric acts as a boundary and to a large extent is a controlled environment. In the case of a building, a modeling discrepancy arises largely due to lack of both an understanding of human activities in the building, and control over the infiltration and natural ventilation strategies (Giridharan *et al.*, 2013). The knowledge of building physics and the performance of buildings in different climates is at a mature state and, as a result, dynamic thermal models are well advanced. Although these models are developed and widely used by engineers, the nature of modern day architectural consultancy has led to the integration of these specialists into the early-stage design process. Some architects integrate environmental modeling into the design process because of their design philosophy. However, many have followed this route to purely fulfil the statutory obligations related to performance evaluation.

Environmental issues cannot be solved at the level of an individual building (Golany, 1996; Oke, 1988; Givoni, 1998). Even the performance of individual buildings should be assessed on an urban design scale. However, by and large, there is no statutory requirement to carry out such an assessment at that level. Furthermore, unlike individual building performance analysis, establishing the boundary conditions for urban analysis is very complex (Oke *et al.*, 1990–91; Oke, 1988; Nichol and Wong, 2005). Most of the available urban design scale climate models (UCL and mesoscale models) are inclined towards atmospheric science (Ooka, 2007; Hidalgo *et al.*, 2008; Mirzaei and Haghighat, 2010). The available research work suggests that on most occasions building physicists and mechanical engineers are not interested in working on this scale, while most atmospheric scientists and climatologists are not interested in the detailed examination of the impact of design elements on climate using these models (Golany, 1996; Herbert *et al.*, 1998; Ooka, 2007; Ali-Toudert and Mayer, 2006; Martilli, 2007). On most occasions engineers are pushed by developers to pursue highly mechanized environmental solutions to meet the building regulation requirements, especially in commercial and institutional buildings. As a result, they opt for highly controlled environments, minimizing the indoor and outdoor interactions, as shown in Chapters 1 and 2. This renders the presence of the surrounding environment irrelevant. Under this assumption, they model single-zone or single-space models with little or no consideration for physical variations in the immediate environment. At the same time, atmospheric scientists and climatologists consider the entire building as one element without considering the variations in geometry, surface material and activities. In tropical research and design this trend is widespread. However, in temperate and cold climates the situation is improved, i.e. building physicists and engineers go beyond the building to integrate passive strategies while atmospheric scientists and climatologists take urban variations into as much account as possible.

On the other hand, most urban designers and planners in tropical cities are not trained to handle canopy layer and mesoscale models. As a result, they are unable to understand the boundary conditions (Fig. 8.6) and assumptions in order to run a model and apply the results in the appropriate context (Adebayo, 1990–91; Giridharan, 2005; Ng, 2012). On most occasions, designers and planners tend to use subjective criteria to evaluate the complex climate premises in order to apply them in their urban development proposals (Evans and Schiller, 1990–91). Such an approach will not help the designer to assess what is causing what, and more importantly to understand to what degree a particular design feature is applicable to a context. To overcome this, designers and planners not only need to train themselves in urban climate modeling but also be involved in model development, linking urban design and planning theories. Compared to a decade ago, currently there is a high level of interest in urban climate modeling (Dimoudi *et al.*, 2013; Futcher *et al.*, 2013; Yang *et al.*, 2011). However, parametrization and integration of critical urban design variables into the models are at an early stage. Most of the work in this regard is taking place in temperate and Mediterranean climate regions (Sham 1990–91; Martilli, 2007; Futcher and Mills, 2013; Roth, 2007). In the tropics, the level of interest is just picking up (Roth, 2007; Emmanuel *et al.*, 2007; Yang *et al.*, 2011; Ng *et al.*, 2012). However, the applicability of these models is limited to the case study location due to the following reasons:

1. the models are not validated against measured data from other similar locations;

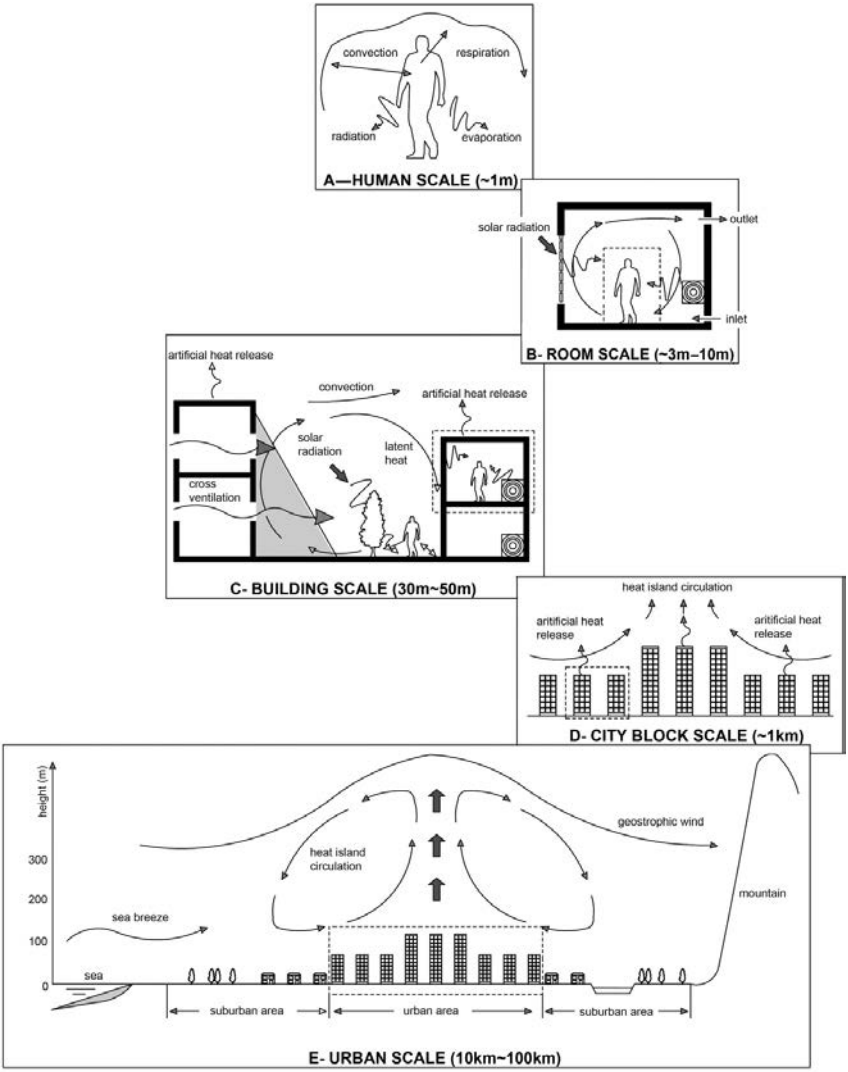


Figure 8.6. Boundary conditions for canopy layer models range from Building (B) to Urban (D) scale. (Source: Adapted from Ooka, 2007)

2. on most occasions, the variables used in the models are unique to that particular case study location; and
3. on most occasions the variables are not related to planning and urban design guidelines/regulations devised for larger contexts.

In the 1990s Sham (1990–91) felt that the findings of temperate urban climate models could be transferred directly without much error or with some modifications to suit local conditions. This is largely due to a lack of research into tropical climates, especially with regard to modeling considerations (Oke *et al.*, 1990–91). Even the available work at that time was largely specific to a city, based on data from standard weather stations. Further, research into these weather data was descriptive and largely unstructured. This resulted in a search for temperate climate research data. However, it is only possible to transfer the temperate climate findings if the order of significance of the climate parameters is similar in both contexts and developments follow similar regulations and development policies. Most importantly, urban design parameters should be truly independent so that effects and their causes are clear. In reality urban design parameters are very much interdependent. Further, research work by Emmanuel *et al.* (2007) and Ng *et al.* (2012) into tropical climates and Dimoudi *et al.* (2013) and Futcher and Mills (2013) into temperate climates indicate that the order of significance and the degree of independence of the parameters are substantially different in the two contexts. Furthermore, upper boundary conditions for urban canopy models depend on the Wake layer. The characteristics of this layer in a tropical climate vary substantially from that of a temperate climate, especially in the context of torrential rains, rain storms (mainly a coastal phenomenon) and topography. As a result, transferring temperate findings without adequate control over the boundary conditions and parametrization could misguide the development. It could indeed be said that this is taking place to some extent in the way international styles are currently being adapted. Such adaptation of international style has led to very energy-intensive urban environment, especially in terms of space conditioning. Therefore, it is very important that models are developed that take into account contextual changes, especially in terms of boundary conditions and tolerance level.

Urban climate modeling needs an interdisciplinary approach, covering meteorology, urban planning, urban design, landscape, architecture and building physics (Sundersingh, 1990–91; Oke, 1987; Golany, 1996; Giridharan, 2005). Meteorology (atmospheric science) has well-established theories to explain the environmental changes, but it is in planning and urban design where established premises to link the physical design issues with meteorological theories are lacking. Urban design and planning tend to look at parameters within a very loose conceptual framework. Further, social, economic and environmental issues are considered as three different domains and are linked superficially without analysis of any underlying interdependency at both a fundamental (micro) as well as higher level, such as regional (meso). This is not helpful when defining urban design parameters for the purpose of modeling, where clear parametrization is essential for planners and urban designers to validate a model in different contexts. This author is of the opinion that integrated and regenerative premises have great potential to create a uniform basis for parametrization on an urban design scale.

The integrated premise considers urban environment as stocks, flows and patterns (EGUE, 1996). The stocks are tangible features such as buildings, land, open space, and streets. The flow accounts for all pressures from urbanization, such as household trends, demand for energy, transport, materials, and waste. The patterns are the structure of all urban and rural forms, neighborhood design and street layout. With an integrated approach, the urban environment is broken up into tangible elements and then analyzed. A regenerative approach, on the other hand, is based on ecological theory (Lyle, 1994), according to which the fundamental order does not entirely lie at a molecular level but is at every level. In other words, everything is linked to every other thing. The ecological theory states that the ecosystem has three orders, namely structural, functional and locational (Lyle, 1994). The structural order specifies the ongoing interaction of each species with others. The functional order explains the flow of energy and material, while the locational order determines topography, soil and climatology. These elements are all linked to one another. Thus the premises of integration help to identify the urban parameters while the regenerative approach underlines the importance of interdependence. Both these premises consider the environment as the primary base, and social and economic factors as sub-bases within that primary base. This aids the examination of social and economic parameters from an environmental perspective. Most importantly, both these premises are in line with the surface energy balance model advocated by Oke (1988).

8.5 Urban Canopy Layer Modeling Options

The urban canopy layer modeling approach could be classified as wind tunnel, statistical, and mathematical (Bornstein, 1986; Taesler, 1986; Giridharan *et al.*, 2007; Swaid and Hoffman, 1990; Oke, 1988; Mirzaei and Haghighat, 2010). The scaled physical models are generally tested in wind tunnels. In advanced wind tunnel models, an electrical heater or hot wire is used to simulate the changes in outdoor temperature while passive smoke is administered to visualize the flow pattern. Although scaled physical wind tunnel modeling is less complex compared to the mathematical approach, achieving similarity between the actual environment and that in a wind tunnel is extremely difficult, especially in tropical conditions where precipitation and topography play a major role (Bornstein, 1986; Givoni, 1986; Nieuwolt, 1986). The scope for sensitivity analysis and testing for alternative options is also limited. However, it is still very useful to study the wind shadow in complex urban environments.

The statistical approach generally uses either bivariate or multiple regression techniques (Giridharan *et al.*, 2007; Yang *et al.*, 2011). This is one of the oldest approaches to urban climate modeling. The data for modeling are gathered through field measurements, remote sensing and small-scale models (Mirzaei and Haghighat, 2010). Prior to advancements in 3D computer modeling, a statistical approach was commonly used by urban climate researchers who were focusing on urban morphology-related research. More recently, however, a neural network technique has been used as a statistical approach (Kolokotroni *et al.*, 2009). Such statistical approaches have been used largely due to the flexibility in incorporating context-specific variables. Furthermore, these models do not require large computing power; however, they do require good data to develop a good predictor equation (Bornstein, 1986; Oke, 1988). The dataset should be able to capture all spatial and temporal changes (Giridharan *et al.*, 2007). However, these models do not explain the physical process; they only explain the relationship in terms of changes in independent and dependant variables. In statistical models, if geographical and seasonal variations are controlled, then the changes in outdoor temperature could be explained using on-site variables with reasonable accuracy (Yang *et al.*, 2011, Giridharan *et al.*, 2007). Nevertheless, statistical models every so often encounter a co-linearity problem. This is largely due to a lack of truly 'independent' variables in urban morphology and climatology studies. However, by disaggregating data into seasonal and replacing the interdependent variables with proxy variables, this problem can be overcome to a large extent (Giridharan *et al.*, 2007; Yang *et al.*, 2011). Although the statistical models incorporate urban design variables, the data are derived from only a few case studies. Therefore their applicability to another location is limited.

In contrast to statistical models, mathematical models explain the physical process. These models are classified as analytical and numerical models. For example the cluster time thermal constant (CTTC) model, canyon air temperature (CAT) model and Runnal and Oke UHI model are analytical models while computational fluid dynamics (CFD), boundary layer and turbulence treatment model are considered as numerical models. The major difference between a numerical and analytical model is the ability of the numerical model to explain the process in time steps.

The CTTC model was able to capture the impact of aspect ratio and street orientation; however it does not capture the impact of anthropogenic heat, soil moisture conditions, cloud variations and variations in wind speed (Sawid and Hoffman, 1990). The CAT model, which is an extension of CTTC with capabilities to incorporate the weather data from local weather stations, has the potential to predict realistic site-specific temperature in Australian cities (Erell and Williamson, 2006). However, this model was not able to capture the impact of an overcast sky (Kolokotroni *et al.*, 2009). Runnals and Oke's (2000) empirical model predicts the UHI by taking into account multiple controls including time of day, wind speed, cloud cover and rural thermal admittance. This model is based on the measurement of the local physical parameters of Vancouver. As a result, the coefficient is sensitive to particular site characteristics, so they can be applied only to similar conditions (Kolokotroni *et al.*, 2009). By and large, bearing in mind the aforesaid limitations, the CTTC model could be used to assess the impact of urban design features on microclimates in hot arid zones. In addition, the Green CTTC model, which is a modification of the original CTTC model, is capable of capturing the climatic impact of trees on alternative urban design proposals (Shashua-Bar and Hoffman, 2003). However, the application of the Green CTTC model in cloudy and high-density environments is yet to be validated (Giridharan *et al.*, 2008).

The other type of mathematical model is the numerical model and can be classified as 1D, 2D and 3D. 1D models usually have a top and a bottom layer with constant values (Bornstien, 1986). However, there are 1D multilayer urban canopy models and on most occasions they have three layers, representing ground, intermediate-level and a layer immediately above roof level (Ooka, 2007; Rasheed *et al.*, 2011). Table 8.1 shows some of the useful canopy layer models.

Most of the existing urban canopy models have errors in the estimation of short-wave radiation and turbulence estimation, and in certain contexts these are very significant (Rasheed *et al.*, 2011). On most occasions, this error is not noticed due to lack of validations and calibrations. Further, most models do not generate output parameters in line with urban design decisions (Martilli, 2007). Another aspect is that the representation of vegetation (i.e. heat fluxes from vegetation and urban surfaces) is calculated separately and the area-weighted average is used to assess the effective fluxes. However, in reality, vegetation has an influence on both latent and sensible heat fluxes released into an environment (Martilli, 2007). These models are reasonably reliable at predicting the changes in outdoor temperature over homogeneous surfaces in temperate climates. However, these models need further refinement when applied in tropical climates, considering the nature of the wake layer, i.e. the wake layer will have a major influence on the top boundary conditions and it is unrealistic to have a constant value even for a short

Table 8.1. Selected urban canopy models for urban climate and heat island intensity study. (Source: Ooka, 2007)

Model name and developer	Turbulence model	Building area density	Drag coefficient	Radiation Calculation
AIST-CM Kondo and Liu (1998); Kondo *et al.* (2005)	0 equation Gambo (1978)	$a = BPw(z)/((B+W)^2 - B^2Pw(z))$	Fixed value Cdrag = 0.4	Kondo and Liu (1998), Kondo *et al.* (2005)
RAUSSSM Higishima *et al.* (2001)	0 equation Gambo (1978)	$a = B/((B+W)^2 - B^2)$	Maruyama (1991)	Radio City
UCSS Ashie *et al.* (1999); Ashie and Vu Thanh (2004)	k-ε two equation Vu Thanh *et al.* (2000, 2002)	$a = \sqrt{\text{bldr}}$	Fixed value	Ashie *et al.* (1999); Ashie and Vu Thanh (2004)
Kusaka *et al.* (2001)	Single layer	Single layer	Single layer	Sakakibara (1995)
SUMM Kanda *et al.* (2005a & 2005b)	Single layer	Single layer	Single layer	Kanda *et al.* (2005a)
Martilli *et al.* (2002)	k-l two equation Bougealt and Lacarrere (1989)	$a = 4\xi B/(B+W)^2$	Fixed value Cdrag = 0.4	Martilli *et al.* (2002)
Hiraoka *et al.* (1989)	k-ε two equation	$a = 2B/((B+W)^2 - B^2)$	—	—
Ooka *et al.* (2004)	k-l two equation Yamada and Bunker (1988)	$a = 4B/(B+W)^2$	Fixed value Cdrag = 0.4	Kondo and Liu (1998)
TEB Masson (2000)	Single layer	Single layer	Single layer	Masson (2000)
Arnfield (2000)	Single layer	Single layer	Single layer	Arnfield (2000)
Best (2005)	Single layer	Single layer	Single layer	Heat balance in urban canopy

period in the tropics, considering the frequent torrential rain and topography-induced wind.

The dynamic differential models are 2D and 3D (Bornstien, 1986). The 2D models explain changes in horizontal and vertical directions by incorporating lateral boundary conditions and horizontal diffusion coefficients. Unlike in temperate zones, and with the exception of countries like Japan, Hong Kong, and Singapore, the tropical zone lacks detailed and structured field measurement data to derive necessary horizontal boundary conditions. Some tropical cities do not even have a proper meteorological station to collect basic climate data. However, 2D models are better than 1D since they include the temperature gradient in vertical circulation (Bornstien, 1986). Further, results are valid only for straight-line settings. However, tropical settings have complex topography and, as a result, the horizontal wind movement will be very much different from a straight-line setting. In addition, most of the early-stage 2D models were focused on the mesoscale. These models tend to represent the UCL as one element, i.e. a flat element of appropriate proportion with a constant specific heat capacity (Ooka, 2007; Martilli, 2007). This approach is acceptable for weather predictions, but not, however, for urban design. These models are indeed capable of predicting changes in outdoor temperature, but on most occasions they tend to underestimate the values especially in the absence of proper representation of sea breeze and inland penetration (Martilli, 2007). Nevertheless, 3D models are capable of overcoming this constraint and explain the changes in complex urban geometry, but they do require large computer power. Further, a resolution of 1 m is necessary to reasonably represent the heterogeneities in the urban area (Martilli, 2007) and an urban model of such resolution will require several years to carry out a simulation on a normal desktop computer. In this scenario proper input/output parametrization is essential to overcome this problem.

The CFD models are 3D and often coupled with radiation and conduction calculation, providing output in the form of flow pattern, temperature, and aging of air (air quality) (Ooka, 2007). From the urban design point of view, microscale (1000 m) CFD models are reliable enough to assess the environmental changes within the UCL, especially the changes in outdoor temperature. The changes in outdoor temperature are an outcome of several phenomena, ranging from human metabolism to the interaction of atmospheric parameters (Mirzaei and Haghighat, 2010). These activities take place within different time scales and spatial resolutions (Oke, 1987; Givoni, 1998; Hidalgo *et al.*, 2008; Mirzaei and Haghighat, 2010). To achieve accurate results, the simultaneous integration of all these phenomena is required (Fig. 8.7), i.e. the holistic modeling approach should link human-scale comfort to building-scale, which in turn should link to microscale and finally to mesoscale models (Ooka, 2007). However, it is difficult to develop a comprehensive database incorporating all the complex parameters due to weaknesses in the premises, especially the inconsistency with respect to different contexts and scales (Mirzaei and Haghighat, 2010; Hidalgo *et al.*, 2008). CFD models could be run over a scale of a few kilometers using currently available powerful computers (Ooka, 2007) but not on normal desktop devices.

Most of the CFD microclimate models do not have the capability to assess outdoor thermal comfort since they do not calculate the radiant fluxes reaching the human body within complex urban environments (Ali-Toudert and Mayer, 2006). Fundamentally, these models do not calculate the mean radiant temperature, but instead rely on factors such as measured wind speed, air temperature, and humidity. However, models such ENVI-met have the built-in capability to assess the thermal comfort in the form of a physiologically equivalent temperature (PET) index, which is a function of mean radiant temperature. ENVI-met is a 3D model that takes into account the wind flows, turbulence, radiation fluxes, temperature and humidity based on the fundamental laws of fluid dynamics and thermodynamics (Ali-Toudert and Mayer, 2006). Furthermore, ENVI-met is not only capable of handling various urban geometry but also vegetation influence. Additionally, ENVI-met is capable of assessing the outdoor temperature changes at a resolution of 0.5 m grid (Emmanuel *et al.*, 2007). The drawback to ENVI-met, however, is that buildings are modeled at multiples of grid cell and the walls have no thermal mass, i.e. heat stored in the wall is not considered. As a result, daytime mean radiant temperature could be overestimated as all the absorbed radiation is assumed to be warming the surface while nighttime mean radiant temperature is underestimated since no heat is stored during the day to radiate during the night. Furthermore, all the buildings have a constant albedo and thermal transmittance value. Another shortcoming of ENVI-met is that the influence of sea breeze and mountain winds cannot be simulated (Emmanuel *et al.*, 2007). In addition, if ENVI-met runs on personal computers, the schemes of short- and long-wave for complex geometries are difficult to generate since a few gigabytes of RAM for a medium-sized model are required. This is because every surface needs to know the state of each other surface at any given time to simulate the surface energy balance. ENVI-met also appears to have overlooked the criticality of anthropogenic heat in urban climate modeling. Despite these drawbacks, however, ENVI-met is currently widely used in urban climate modeling.

3D modeling techniques have advanced substantially and tools are also becoming very user-friendly. Thus, dynamic thermal models such as IES (integrated environmental solutions) and Design-Builder are currently being used for urban energy and climate modeling. For example, Futcher and Mills (2013) have modeled the sensitivity of the aspect ratio in determining the energy consumption of a street block using IES thermal modeling. For the model to reliably predict energy consumption, construction information, set point temperature, internal gains, infiltration and other factors for each building have to be reasonably accurate. On most occasions values for each of these parameters have been kept constant throughout the modeling environment. Such models will under- or overestimate energy consumption, depending on seasonal conditions. Furthermore, the IES takes into account shading and radiation exchange from adjacent buildings, yet it is not capable of capturing the impact of multiple reflections from an urban canyon. The potential of IES to capture the effect of wind, especially turbulence, at different heights is limited. Design-Builder has the capacity to capture outdoor wind flow pattern, but the external CFD does not take into account the thermal properties of the topography and ground cover as it only looks at the reflective properties. Normally, in Design-Builder, models are done for seven multiple reflections, but in a deep urban canyon the reflection dies only after 20 times.

8.6 Parametrization of Critical Urban Variables for Modeling

It is now well-established that to understand urban climate changes, better quantification of the impact of density, land use, thermo-physical characteristics, geometry, local energy consumption, anthropogenic heat release, heat source, and cool sink is essential (Oke, 1988; Givoni, 1998; Santamouris, 2001; Emmanuel, 2005; Giridharan *et al.*, 2007; Yang *et al.*, 2010; Ng *et al.*, 2012; Dimoudi *et al.*, 2013). The surface energy balance is fundamental to urban climate. However, to identify and characterize the surface is a major issue, especially in the presence of vegetation. Vegetation has multiple influences on urban climate and it varies with space and time. Furthermore, the urban surface is made of various sizes, shapes, and composition within a variety of urban forms. As a result, assigning correct surface data for climate analysis is a great challenge (Oke, 1988). This is a major issue if we are to use statistical models or analytical models similar to CTTC, and is largely due to scale and the heterogeneous nature of the urban environment. In order to use existing credible statistical and other mathematical models for urban design initiatives, substantial work needs to be carried out prior to the modeling exercise to transfer the urban design concepts into modeling parameters. This complex transfer process is essential due to the presence of model parameters at a fundamental level of atmospheric physics.

Urban design initiatives work at a higher order of fundamental level as conceptualized in the integrated and regenerated approaches. It is difficult to quantify them in an order and a level similar to atmospheric science parameters. Furthermore, if we keep the parameters too general, establishing the boundary conditions and measuring these parameters are even more difficult (Nichol and Wong, 2005; Giridharan *et al.*, 2007). For example, on most occasions, information on anthropogenic heat and density will have to be sourced from institutional data and these data are available on a planning-boundary scale; these statutory boundaries are not compatible to urban climate modeling grids. Furthermore, urban design decisions are taken along the lines of variation in thermal mass, skyline and density. In urban design, for example, thermal mass is not conceptualized in terms of the contents of a wall, but rather a relationship between height and total floor area (Knowles, 1977; Giridharan *et al.*, 2007). Similarly, the skyline is assessed as a function of massing, not based on turbulence and drag effect. In an individual space, thermal comfort is assessed in terms of thermal transmittance of the wall. The equivalent initiative at urban design could come in the form of aspect ratio, which is a function of the ratio of building height to street width. Therefore, on most occasions, urban design initiatives are made of higher order variables (Golany, 1996; Givoni, 1998). Such conceptualization argues for collective design variables (Giridharan, 2005). In this scenario, for the purpose of statistical modeling, manmade factors in urban environments could be classified as form-fabric, land-use, and density descriptors. These latter descriptors are generally represented by more than one design variable, though it may be said that a descriptor is nothing but the collective design variable. At the same time, man-made factors interact with natural descriptors, which in turn are represented by climatic and geographical parameters.

Urban forms can be classified as compact, dispersed and clustered (Golany, 1996). However, modeling these forms requires defining them in the context of collective urban geometry within the microclimate boundary. For example, in the high-rise, high-density environment of Hong Kong, the microclimate boundary was found to have a 15 m radius (impact radius), i.e. the microclimate boundary could be confined to one-and-a-half block distance or between two streets. The built form-fabric descriptors help to frame the form in the respective context. The built form-fabric descriptor (Table 8.2) is a set of design variables for a building or a group of buildings, which influences the thermal comfort within the microclimate boundary. For example, the surface area to volume ratio is a very common

Table 8.2. Selected built form-fabric descriptors. (Source: Knowles, 1977; Golany, 1996; Giridharan, 2005; Giridharan *et al.*, 2007; Shashua-Bar *et al.*, 2006; Yang *et al.*, 2010)

Descriptor	Description	Premises	Source for information
Glass to wall area ratio	The ratio of glass area on all the façades to total surface area of all the façade within the environmental impact radius.	If the glass to wall area ratio increases the outdoor temperature will increase. Any value higher than 30% could have significant impact on outdoor temperature. However the real impact depends on the sky view factor.	Generally the statutory plans hold the information on footprint and building heights. Photographic survey could be used for assessing the glazed area.
Plan type or structure	The general categorizations are closed, semi-closed and linear, open linear etc. This is generally assessed based on average length to average width ratio in the respective category within the impact radius	This captures the characteristics of the plan form. Generally, this is identified in relation to level of wind shadow. In the tropics, the more linear the form (in the respective category), the lower the impact on the increases in the outdoor temperatures. This descriptor is more suitable for cross comparison of large developments with typical forms.	Generally the statutory plans hold information on plan characteristics (footprint).

(*Continued*)

Table 8.2. (*Continued*)

Descriptor	Description	Premises	Source for information
Total height to total floor area ratio	This ratio will help to assess the influence of slenderness on cooling the mass of the overall form within the impact radius. In the absence of total height and total floor area information, average height to foot print area could use.	This is a proxy for thermal mass. In the tropics, the higher the slenderness, the lower the impact on the increases in the outdoor temperatures. The effect amplifies if the comparison is done under constant floor area.	Generally the statutory plans hold information on footprint and building heights.
Surface area to volume ratio	The ratio of surface area of all the façades to total volume of all the buildings within the environmental impact radius.	Increase in surface area will increase the absorption of shortwave radiation. This is a better representation of thermal mass, however sourcing volume information could be difficult where internal level changes are frequent. In the tropics, the lower the ratio, the lower the impact on the increases in the outdoor temperatures.	The surface area information could be extracted from statutory plans. However details plans/sections of the building or visit the site only could reveal volume information.

Quality of façade material or faced albedo	The overall albedo of the façade is determined by taking the area weighted average albedo of the material in the façade within the impact radius. The albedo is the ratio of incoming to outgoing radiation.	The higher the albedo, the lower the impact on the increasing of the outdoor temperature. However the actual impact of albedo will depend on the urban geometry, especially the sky view factor.	Photographic survey could be used to identify the different materials and their coverage in the façade. This proportion could be applied to statutory plan based façade area. The albedo for different material could be extracted from established building material or environmental design guides.
Volume of the vertical punch to volume of the mass ratio	This is the ratio of the volume of the punch to volume of the mass within the impact radius.	This represents the wind velocity enhancement in relation to degree of walling effect. The higher the porousness of the mass, the lower the impact on the increases in the outdoor temperatures.	Logical deduction from information extracted from statutory plans and photographic survey.
Façade length to average building height ratio.	Ratio of the length of the facade to average height of the buildings within the impact radius.	This is a proxy to represent the urban ventilation potential. The lower the ratio, the lower impact on the increasing of the outdoor temperature.	Logical deduction of information extracted from statutory plans and filed observation.

(*Continued*)

Table 8.2. (*Continued*)

Descriptor	Description	Premises	Source for information
Thermal conductivity of the external wall surface	The overall thermal conductivity of the external wall surface is determined by taking the area weighted average thermal conductivity of materials in the façades within the impact radius.	The materials with higher thermal conductivity will increase the surface temperature compared to materials with lower thermal conductivity. The higher surface temperature has potential to increase the outdoor temperatures.	Photographic survey could be used to identify the different materials and their coverage in the façade. This proportion could be applied to statutory plan based façade area. The conductivity for different material could be extracted from established building material or environmental design guides.
Non-residential floor area to total floor area ratio	Any space used for commercial, office and institutional activities are considered as non-residential. All types of hotels too are considered as non-residential. However hostels are considered residential.	This is a proxy for heat rejection capacity of the mass. This is generally useful to represent the commercial scale use of air conditioning. Generally, the higher non-residential component will lead to higher outdoor temperatures.	Logical deduction from information extracted from — statutory plans and filed observation and photographic survey.

Non-residential façade area to total façade area ratio	Façades of any space used for commercial, office and institutional activities are considered as non-residential. All types of hotels too are considered as non-residential. However hostels are considered residential.	This is another proxy for heat rejection capacity. This could be used in situations where floor area information is not available. This is more relevant in places where the façade has elements such as neon lights etc. Generally, the higher non-residential component will lead to higher outdoor temperatures.	Logical deduction from information extracted from statutory plans and filed observation and photographic survey.

built form-fabric descriptor, but this is not of an individual building façade, rather the entire façade within the boundary.

The land use descriptor (Table 8.3) deals with ground coverage pattern. Vegetation is a primary variable that influences the ground coverage in the context of urban climate (Oke, 1987; Givoni, 1998; Giridharan *et al.*, 2008). Water and the reflective property of the material also influence the ground coverage pattern. Vegetation primarily improves the microclimate by (1) intercepting solar radiation impinging on the surfaces, which in turn will result in low cooling load and anthropogenic heat release; (2) shading surfaces that will consequently have low surface temperature resulting in low intensity of long-wave radiation; (3) lowering of air temperature through evapotranspiration; and (4) latent cooling through addition of moisture (Dimoudi and Nikolopoulou, 2003). Although there is substantial research into the influence of vegetation on outdoor climate, specific design information related to location, size and type of vegetation is limited (Givoni, 1998; Ng *et al.*, 2012; Giridharan *et al.*, 2008).

The density descriptor (Table 8.4) is a set of design variables that deals with the population. For example, in the early days, researches into the UHI mostly focused on population density (Landsberg, 1981; Oke, 1987). These studies found that there is a critical link between density and the nature of anthropogenic heat release. Although studies in the last decade have shown a weak correlation between UHI and population, there exists a strong correlation in high-rise, high-density environments (Santamouris, 2001). For example, anthropogenic heat release in Hong Kong is directly proportional to population due to high use of air conditioning. However, assigning the anthropogenic heat data to a population that is being defined by the urban climate boundary is a great challenge; i.e. the population data refer to a statutory boundary. In this scenario it is important to select a parameter that is not constrained by the character of institutional data. At times, however, this problem could be dealt with by establishing proxy or dummy variables (Giridharan *et al.*, 2007).

The natural descriptor (Table 8.5) covers variables related to geography, topography and natural forces. In terms of atmospheric conditions, wind velocity plays a major role in modifying the

Table 8.3. Selected land use descriptors. (Source: Oke, 1987; Huang *et al.*, 1987; Givoni, 1998; Stone and Rodgers, 2001; Giridharan, 2005; Emmanuel and Johansson, 2006; Giridharan *et al.*, 2007; Yang *et al.*, 2010; Ng *et al.*, 2012)

Descriptor	Description	Premises	Source for information
Surface albedo	Ratio of incoming to outgoing radiation. Outgoing radiation is a function of characteristics of the horizontal surface within the impact radius.	Generally horizontal surfaces at ground level such as roads, pavements, green areas are considered. Higher surface albedo will lead to lower outdoor temperatures. However, soil moisture has a significant impact on the behavior of ground surface materials. For example, higher albedo material on dry ground could lead to higher outdoor temperatures.	Photographic survey could be used to identify different materials and their coverage on the horizontal surface. This proportion could be applied to statutory plan based façade area. Albedo for different material could be extracted from established building material or environmental design guides.
Green to open space ratio	Ratio of 'green area' to open space within the impact radius. 'Green area' comprises any type of vegetation, including grass lawns.	The higher the ratio, the lower the outdoor temperature. However, sky view factor has a significant impact on this descriptor. A lower ratio in a lower sky view factor location has higher potential to reduce the daytime temperature than higher ratio in a higher sky view factor location.	Aerial view images could be used to identify green coverage within the impact radius. Statutory plans could be used to identify open areas and apply the vegetation proportion based on aerial view image to extract the vegetation area.

(*Continued*)

Table 8.3. (*Continued*)

Descriptor	Description	Premises	Source for information
Ratio of average canopy area to average height of the trees	Ratio of average canopy area of trees to average height of those trees within the impact radius.	Useful to differentiate the impact of less dense canopy over a dense canopy or an open area covered with palm trees and another with rain trees. The larger the ratio, the lower the impact on outdoor temperature increases. This should be applied to plants over one meter height, otherwise the impact on the shading is marginal.	Field survey along with canopy view/sky view images could help assess this factor.
Distance between vegetation pockets	Useful to assess the impact of multiple vegetation points within the impact radius.	Pocket parks spread over the urban area have a more significant impact on lowering the outdoor temperature than a large park located in one corner of the same urban area. The lower the distance, the lower the impact on outdoor temperatures.	Aerial view image in conjunction with a statutory plan could help to assess the distance of the pocket parks

Built up ratio	Ratio of artificial surface to open area within the impact radius	Generally, artificial surfaces have a higher surface temperature compared to natural surfaces. Further, they also radiate stored heat back into the environment. Therefore, the larger the ratio, the higher the impact on outdoor temperatures.	Applying proportions of the artificial materials based an aerial view image and a photographic survey on to a statutory plan could help to extract the areas.
Vegetation density	Leaf area index or the canopy cover could form a proxy to explain the impact of vegetation density.	This is an alternative variable to ratio of average canopy area to average height of trees. The larger the density, the lower the impact on outdoor temperatures. Any vegetation above one meter should be considered for this descriptor.	The field survey along with canopy view/sky view images using a fisheye lens camera could help assess this factor.
The street structure	Dummy variable to represent the porousness of the fabric. If streets within the impact area are aligned towards prevailing wind direction the variable should be one otherwise zero.	The larger the porousness the better the ventilation potential. Therefore, the larger the porousness, the lower the impact on the increases in the outdoor temperatures, as long as substantial proportion of the streets are aligned towards the prevailing wind direction.	Information from observatory and statutory plans could be used to determine the value.

(*Continued*)

Table 8.3. (*Continued*)

Descriptor	Description	Premises	Source for information
Footprint of the building	Proxy to represent the massing of building in the absence of credible information related to massing within the impact radius	The larger the footprint of the building, the higher the impact on outdoor temperatures.	Extraction of information from statutory plans.
Proximity to heat sink	Heat sinks are big water bodies such as lakes, rivers, sea, and forest, country park etc. The perpendicular distance to bank or to the boundary is considered.	The shorter the distance, the lower the impact on outdoor temperatures. In the statistical models it is better to input the inverse of the distance.	Extraction of information from statutory plans and aerial images.

Table 8.4. Selected density descriptors. (Source: Oke, 1987; Stone and Rodgers, 2001; Santamouris, 2001; Giridharan, 2005; Giridharan *et al.*, 2007; Gago *et al.*, 2013; Yang *et al.*, 2010; Ng *et al.*, 2012; Wong *et al.*, 2011)

Descriptor	Description	Premises	Source for information
Size of the town	Offsite variable that has indirect influence on the changes in the on-site outdoor thermal comfort. The area of the town is considered.	Larger towns will have large built-up areas. Therefore, the larger the town, the higher the impact on outdoor temperatures. This useful in cross-sectional analysis.	Information from statutory plans.
Density of the built-up area	This basically refers to plot ratio. This is a proxy for local population.	Higher density will lead to higher built-up areas and higher energy consumption. Therefore, the higher the density, the higher the impact on outdoor temperature. This is useful in cross-sectional analysis.	Information from statutory plans.
Sky view factor	Amount of sky visible in the hemisphere with respect to reference point. This is a proxy for local density. However, this is more useful to indicate level of short-wave radiation coming in and amount of long-wave radiation lost to night sky (natural descriptor).	The sky view factor will ultimately decide the quantum of radiation entering and leaving the environment. The higher the sky view factor, the higher the impact on the daytime outdoor temperatures. However, the higher the sky view factor, the lower the impact on the nighttime outdoor temperatures. At the same time, cloud cover could override the influence of sky view factor.	Fisheye lens image taken 1 m above the ground with respect to point of measurement could be used to derive the sky view factor or apply geometrical method on to a statutory plan.

(*Continued*)

Table 8.4. (*Continued*)

Descriptor	Description	Premises	Source for information
Average height of buildings	Proxy to represent the local density and wind breaks. However, this should be used in the absence of any other variables to capture the density effect.	Suitable for cross-sectional analysis of different urban canyons. In general, higher heights will lead to lower daytime temperatures and higher nighttime temperatures.	Information from statutory plans and field observation.
Subdivision of the building lots	Number of plots within the impact radius. This is a proxy to represent the intensity of urban land utilization.	Suitable for cross-sectional analysis of large urban areas. In principle, large number of subdivisions will lead to large proportion of artificial surface. Therefore, the larger the number of subdivisions, the higher the impact on the increases in the outdoor temperatures.	Field observation and statutory plans.
Intensity of human activities	Dummy variable that captures the urban operation pattern. The variable will be one if the urban area is in full operation both in day and night. Otherwise zero.	Suitable for cross-sectional analysis. The urban area which operates at high intensity during both day and night will have higher impact on increasing the outdoor temperature, especially the nighttime outdoor temperature	Field observation and local authority policy.

Location quotient (LQ)	This will capture the influence of territorial or regional impact. This is a function of population at different levels	LQ = (PI/PN)/(PL/PT). PI = population within the impact radius. PN = population within the neighborhood or large development area. PL = population in the local area, the boundary for the local area is a large water body, forest, mountain or combination of these. PT = population of territory or region. Territorial population has an impact on the outdoor temperature of a particular place. Territorial impact is represented through the LQ. If the LQ value is high, territorial impact on the point of reference is low.	Combination of statutory plans and census data could be used to determine the population.

(*Continued*)

Table 8.4. (*Continued*)

Descriptor	Description	Premises	Source for information
Aspect ratio	Average building height to width of the street ratio. This is a proxy for sky view factor and density	If the aspect ratio is high, the sky view factor is low. Similarly, if the aspect ratio is low, the sky view factor is high. Therefore higher aspect ratio will lead to lower daytime outdoor temperatures and higher nighttime temperatures.	Field observation and statutory plans.
Emission index (EI)	This index captures the heat emitted from space-conditioning units and cooking.	EI = (AEN/PN)*PI. AEN = average energy consumption in the neighborhood. PN = population in the neighborhood. PI = population within the impact radius. The EI is a function of per capita energy consumption.	Deduct from census statistics or utility records or construct the energy consumption based floor area using local or regional standards.
Income category	This dummy variable captures the impact of lifestyle. If the impact radius is dominated by middle and upper income, then use the value one, otherwise zero.	Suitable for cross-sectional analysis. It is assumed that the higher income people consume higher amount of energy to maintain their lifestyle, especially in terms of space conditioning.	Field observation, census data and local authority classifications.

Table 8.5. Selected natural descriptors. (Source: Arnfiled, 1982; Oke, 1987; Givoni, 1998; Santamouris, 2001; Giridharan, 2005; Giridharan *et al.*, 2007; Emmanuel *et al.*, 2007)

Descriptor	Description	Premises	Source for information
Wind velocity	If the wind velocity is higher than 5 m/s, the urban heat island is very weak.	Higher wind velocities will lead to lower outdoor temperatures.	Should be measured locally using anemometer.
Cloud cover	Measured in Oktas. 8 Oktas will result in 100% cloudy skies and 0 Oktas will result in 100% clear skies.	Cloud cover will determine the amount of radiation reaching the earth surfaces and amount of radiation lost to the clear skies. For example 100% cloudy condition will reduce the daytime temperatures while increasing the night time temperatures. Generally this variable is used to control the sample.	Difficult to measure at each reference point due to equipment constraints. Therefore, observatory values are used.
Altitude	Higher altitudes have the potential to capture higher wind velocity and lower the air temperature.	Generally high variations in the landforms could be found in the higher altitudes. Further, the landform also help to deflect the solar radiation. Therefore, for every 100 m altitude there is a drop of 1°C (approximately).	Statutory contour maps or use an altimeter.

(*Continued*)

Table 8.5. (*Continued*)

Descriptor	Description	Premises	Source for information
Latitude	Useful variable for cross-sectional study or comparing two different locations.	Suitable for cross-sectional analysis. It will capture the geographical influence on the outdoor temperature.	Use information from Google Earth maps.
Solar radiation intensity	Captures the impact of incoming radiation.	Main driving force behind outdoor temperature. This could vary substantially in line with the variations in urban settings.	Should be measured locally using a pyronometer at different reference points.
Surface water level	Based on the water table value within the impact radius. A proxy for soil moisture condition.	More suitable for cross-sectional analysis. This also influences the albedo level. Higher soil moisture levels generally lead to lower ground temperatures. Lower ground temperature will result in lower outdoor temperatures.	Obtain information from local geological maps.
General topography of the area	Dummy variable to represent the landforms. If the area under consideration has substantial level differences the value is one, otherwise zero.	Level differences in landform could lead to positive and negative effects in the atmosphere. These positive and negative effects could drive the wind movement. Therefore land with substantial level differences could lead to higher wind movement resulting in lower outdoor temperature.	Field observation and statutory contour maps.

nocturnal heat island in temperate climates. However, in the tropics, observations in Kuala Lumpur have especially revealed lapse rate and cloud amount as the most important parameters in determining the nocturnal heat island (Sham, 1990–91). The influence of cloud cover was evident in Hong Kong as well (Giridharan *et al.*, 2007). However, it is difficult to get information on cloud cover and lapse rate in most of the tropical cities. Therefore, two primary climate parameters that are studied to assess the urban climate are air temperature and wind velocity (Dimoudi *et al.*, 2013, Ng *et al.*, 2012; Giridharan *et al.*, 2006; Yang *et al.*, 2011).

All these descriptors are not critical at all locations. For example Wong *et al.* (2011) believe that the three key parameters affecting changes in outdoor temperature are buildings, green spaces and pavement. Yang *et al.* (2011) were able to explain the changes in outdoor temperature in a high-rise housing development in Shanghai using sky view factor, total site factor, tree view factor, green plot ratio, green cover ratio, daytime wind velocity, solar radiation intensity and floor area ratio. Table 8.6 presents values for some selected parameters for residential development in Hong Kong's coastal area.

On-site variables are capable of capturing changes in the outdoor temperature in an environment and at times they create their very own microclimate (Giridharan *et al.*, 2007; Jusuf *et al.*, 2007). However it is important to explain what aspect of the building (height, area, volume), and green area (density of vegetation, extent of vegetation, location of vegetation) is causing changes in outdoor temperature. The level of dissection of a parameter will depend on the character of the environment. For example, high vegetation locations should follow greater characterization of the vegetation parameter. However, geographical influences could be more prominent in contexts where an urban area is abutting a mountain or coastal area (Sham, 1990–91; Adebayo, 1990–91; Tso, 1996; Giridharan *et al.*, 2007; Chow and Roth, 2006). In general, the model must have parameters to represent both micro- and mesoscale variations. However, if changes in one of these parameters are negligible then it should neither underestimate nor overestimate the influence of other parameters. Further, in high-rise, high-density environments, the behavior of one parameter will

Table 8.6. Mean values of selected parameters for residential developments in the coastal area of Hong Kong. (Source: Giridharan *et al.*, 2007)

	Name of the Residential Estate						
Variables	Wah Fu- 1	Wah Fu- 2	Repulse-109	Repulse-101	Ma Hang	Butterfly	Wu King
1 Solar radiation intensity between 13 h and 17 h in Mj/m^2	2.170	1.590	2.390	2.360	2.610	2.047	2.177
2 Wind velocity at site between 13 h to 17 h in m/s	0.8	1.1	1.1	1.4	0.8	1.1	1.2
3 Wind Velocity at site between 18 h to 22 h in m/s	0.8	0.8	0.7	1.0	0.4	1.0	1.3
4 Average height to total floor area ratio	0.034	0.0174	0.034	0.123	0.017	0.019	0.0618
5 Sky view factor	0.28	0.32	0.34	0.32	0.27	0.27	0.27
6 Surface albedo	0.21	0.19	0.17	0.18	0.16	0.18	0.12
7 Altitude in m	26.8	64.5	34.9	37.5	36.9	5.0	4.1
8 Proximity to sea (heat sink)	0.010	0.0028	0.005	0.005	0.002	0.002	0.0024
9 Vegetation below 1 m in height in %	11.8	4.5	19	5.4	19.7	8.3	11.9
10 Vegetation above 1 m in height in %	20.7	9.3	16	19.6	21.5	16.3	10.2
11 Total non-residential to total floor area ratio	0.035	0.0993	0.092	0.007	0.000	0.153	0.0311
12 Location quotient	99.07	106.9	59.5	61.85	372.4	5.1	3.43
13 Emission index — day	38.0	38.9	2.6	2.7	11.9	41.2	25.0
14 Emission index — night	70.5	72.2	3.9	3.1	18	76.5	30.5

(*Continued*)

Table 8.6. (*Continued*)

Name of the Residential Estate									
Tsui Ning	Siu Lun	Sun-shine City	New Town	Wo Che	Heng On	Hang Fa Chuen-1	Hang Fa Chuen-2	Taikoo stage-4	Taikoo stage-11
1.360	1.540	2.140	1.870	2.160	1.780	1.420	1.577	1.500	1.960
1.0	0.9	1.3	1.1	0.8	1.7	0.8	0.7	0.5	0.7
0.7	1.0	1.0	1.3	0.4	1.3	1.2	0.5	0.2	0.4
0.0519	0.101	0.0628	0.0159	0.0201	0.0660	0.0559	0.0374	0.0535	0.0043
0.20	0.31	0.29	0.25	0.21	0.29	0.38	0.16	0.16	0.19
0.11	0.15	0.16	0.16	0.18	0.13	0.20	0.17	0.14	0.14
2.3	19.3	16	5.3	6.2	5.3	12.7	9.3	17.6	9
0.0031	0.002	0.0042	0.0040	0.0018	0.0224	0.0036	0.0027	0.0030	0.0031
19.5	25.4	12.2	8.9	12.8	14.6	14.1	13.1	19.13	12.4
12.3	5.4	4.9	10.3	17.9	6.2	6.0	8.0	14.5	24.8
0.0190	0.281	0.3723	0.0710	0.1193	0.0002	0.2095	0.0283	0.3159	0.2447
10.6	104.5	7.1	8.3	131.6	27.3	26.2	8.4	6.9	9.2
42.9	18.6	7.8	21.4	27.5	44.7	39.3	15.8	15.7	34.4
64.34	22.8	10.0	39.7	41.2	54.6	48.0	19.3	19.2	63.9

Note:
(1) Proximity to sea = 1/distance from sea to point of measurement. (2) Due to difficulties in getting the actual floor area in certain buildings in the development, the study uses the footprint as a proxy for the actual floor area.

at times be influenced by another. For example, the cooling capacity of vegetation could be diluted by a low sky view factor (Yang *et al.*, 2011; Giridharan *et al.*, 2007).

Currently, the parametrization of anthropogenic heat and the collection of necessary energy input data are some of the most difficult aspects of urban modeling (Martilli, 2007). Statistical models could use emission and location quotient indexes as proxy for anthropogenic heat (Table 8.4). However, these indices are only suitable for cross-sectional analysis since primary data are aggregated along statutory boundaries. The best way to overcome this problem is to use anthropogenic heat as a controlling variable, i.e. datasets are prepared along different categories of anthropogenic heat such as low, medium and high. Ranges of values for low, medium and high are very much dependent on geographical context and the purchasing power of the urban population.

The existing 3D computer models provide an opportunity to represent urban design initiatives without compromising the concept; however, the output comes in the form of temperature and wind velocity. As a result, the urban designer needs to carryout substantial work after the modeling exercise to relate the results to urban design variables such as density, ground coverage, and vegetation density in order to visualize the impact of regulation and development guidelines. In the case of large urban design projects this requires substantial time and manpower.

8.7 Urban Climate Modeling Futures

This chapter highlights the fact that urban design and urban climate modeling are uncomfortably placed between practitioners and researchers. On most occasions practitioners are of the opinion that urban climate modeling is a constraint to their creativity since models are too scientific. However, with the need for evidence-based global climate change mitigation protocols, urban designers may not be able to hold on to this premise for long. With advancements in modeling techniques, the way forward for urban designers is to develop input/output parameters based on credible environmental approaches such as integrated and regenerative. However, it is important that these parameters are in line with development regulations and guidelines. The definition of these parameters should be such that they could be clearly identified in any environment. However, one has to face inevitable challenges in gathering data in line with these parameters. For a meaningful study there should be substantial variations in the sample (observation points), but there will be difficulty in getting permission from respective authorities for such a wide scope of measurements, surveys and observations, especially in sensitive areas. In most cases the research will have to settle for a selected representative sample (Giridharan *et al.*, 2007). Furthermore, attempts should be made to monitor each sample point for 24 h and the number of monitoring days should be such that it covers all seasonal variations. However, due to logistical constraints it will be difficult to monitor and survey a large number of points simultaneously as well as for 24 h. In this scenario, in each season one needs to monitor and survey simultaneously at least three points with substantial variations. Furthermore, within each day, monitoring and surveying should cover both solar radiation peak periods and peak nighttime activity periods. If the data are collected for different urban settings in line with the parameters outlined in Tables 8.2–8.5, models such as ENVI-met could be validated for different locations. Furthermore, interfaces could be developed to plug in to models such as ENVI-met to generate input/output parameters along urban design guidelines. Professional programs in urban design, too, should promote urban climate modeling-related research and design exercises without confining themselves to conservation and economics.

References

Adebayo, Y.R. (1990–91). Consideration for climate-sensitive design in tropical Africa, *Energy and Buildings*, **15**(1–2), 15–21.

Aida, M. (1982). Urban albedo as a function of the urban structure — a model experiment, *Boundary Layer Meteorology*, **23**, 405–413.

Ali-Toudert, F. and Mayer, F.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**, 94–108.

Ali-Toudert, F. and Mayer, F.H. (2007). Effects of asymmetry, galleries, overhanging facades and vegetation on thermal comfort in urban street canyon, *Solar Energy*, **81**, 742–754.

Arnfield, A.J. (2000). A simple model of urban canyon energy budget and its validation, *Physical Geography*, **21**, 305–326.

Arnfield, A.J. (1982). An approach to estimation of the surface radiative properties and radiation budgets of cities, *Physical Geography*, **3**, 97–122.

Ashie, Y., Vu Thanh, C. and Asaeda, T. (1999). Building canopy model for the analysis of urban climate, *Journal of Wind Engineering and Industrial Aerodynamics*, **81**, 237–248.

Ashie Y. and Vu Thanh, C.A. (2004). Development of the urban climate simulation system for urban and architectural planning Part 2, developing a three-dimensional urban canopy model by space averaging method (in Japanese), *Journal of Architecture, Planning and Environmental Engineering*, **AIJ 586**, 45–51.

Best, M. (2005). Representing urban areas within operational numerical weather prediction model, *Boundary-Layer Meteorology*, **114**, 91–109.

Bornstein, R.D. (1986). "Urban climate models: nature, limitations and applications", in Oke, T.R. (ed.), *Urban Climatology and its Applications with Special Regard to Tropical Areas*, Proceedings of the technical conference organised by the world Meteorological Organisation, WMO-652, Geneva, Switzerland.

Bougealt, P. and Lacarrere, P. (1989). Parameterisation of orography-induced turbulence in a Mesobeta-scale model, *Monthly Weather Review*, **117**, 1872–1890.

Chow, W.T.I. and Roth, M. (2006). Temporal dynamics of the urban heat island of Singapore, *International Journal of Climatology*, **26**, 2243–2246.

Dimoudi, A. and Nikolopoulou, M. (2003). Vegetation in the urban environment: Microclimatic analysis and benefits, *Energy and Buildings*, **35**(1), 69–76.

Dimoudi, A., Kantzioura, A., Zoras, S. *et al.* (2013). Investigation of urban microclimate parameters in an urban center, *Energy and Buildings*, **64**, 1–9.

Emmanuel, R. (2005). Thermal comfort implication of urbanisation in a warm-humid city: the Colombo Metropolitan Region (CMR), Sri Lanka, *Building and Environment*, **40**, 1591–1601.

Emmanuel, R. and Johansson, E. (2006). Influence of urban morphology and sea breeze on hot humid climate: the case of Colombo, Sri Lanka, *Climate Research*, **30**, 189–200.

Emmanuel, R., Rosenlund, H. and Johansson, E. (2007). Urban shading-a design option for the tropics? A study in Colombo, Sri Lanka, *International Journal of Climatology*, **27**, 1995–2004.

Erell, E. and Williamson, T. (2006). Simulating air temperature in an urban street canyon in all weather conditions using measured data at a reference meteorological station, *International Journal of Climatology*, **26**, 1671–1694.

Evans, J.M., Schiller, S.De. (1990–91). Bridging the gap between climate and design: A bioclimatic design course for architectural students in Argentina, *Energy and Buildings*, **15**(1–2), 43–50.

Expert Group on the Urban Environment (EGUE). (1996). *European Sustainable Cities*, Commission of the European Communities, Luxembourg.

Futcher, J.A. and Mills, G. (2013). The role of urban as an energy management parameter, *Energy Policy*, **53**, 218–228.

Futcher, J.A., Kershaw, T. and Mills, G. (2013). Urban form and function as building performance parameters, *Building and Environment*, **62**, 112–123.

Gago, E.J., Roldan, J., Pacheco-Torres, R. *et al.* (2013). The city and urban heat islands: a review of strategies to mitigate adverse effects, *Renewable and Sustainable Energy Reviews*, **25**, 749–758.

Gambo, K. (1978). Notes on the turbulence closure model for atmospheric boundary layers, *Journal of the Meteorological Society of Japan,* **56**, 466–480.

Giridharan, R. (2005). Urban design factors influencing outdoor temperature in high-rise high-density residential development in coastal zone of Hong Kong, Thesis, The University of Hong Kong.

Giridharan, R., Lau, S.S.Y., Ganesan, S. *et al.* (2007). Urban design factors influencing urban heat island intensity in high-rise high-density environments of Hong Kong, *Building and Environment*, **42**, 3669–3684.

Giridharan, R. Lau, S.S.Y., Ganesan, S. *et al.* (2008). Lowering the outdoor temperature in high-rise high density residential developments of coastal Hong Kong: The vegetation influence, *Building and Environment*, **43**, 1583–1595.

Giridharan, R., Lomas, K.J., Short, A. *et al.* (2013). Performance of hospital spaces in summer: a case study of a 'Nucleus'-type hospital in the UK Midlands, *Energy and Buildings*, **66**, 315–328.

Givoni, B. (1986). "Design for climate in hot, dry cities", in Oke, T.R. (ed.), *Urban Climatology and its Applications with Special Regard to Tropical Areas*, proceedings of the technical conference organised by the world Meteorological Organisation, WMO-652, Geneva, Switzerland.

Givoni, B. (1998). *Climate Considerations in Building and Urban Design*, John Wiley & Sons, New York, NY.

Golany, G.S. (1996). Urban design morphology and thermal performance, *Atmospheric Environment*, **30**, 455–465.

Hagishima, A., Tanimoto, J., Katayama, T. *et al.* (2001). An organic analysis for quantitative estimation of heat island by the revised architecture-urban-soil simultaneous simulation model, AUSSSM part 1, Theoretical frame of the model and results of standard solutions (in Japanese), *Journal of Architecture, Planning and Environmental Engineering*, **AIJ 550**, 79–86.

Herbert, J.M., Johnson, G.T. and Arnfield, J. (1998). Modelling the thermal climate in city canyon, *Environmental Modelling Software*, **13**, 267–277.

Hidalgo, J., Masson, V., Baklanov, A. *et al.* (2008). Advances in urban climate modelling, trends and directions in climate research, *Annals of the New York Academy of Science*, **1146**, 354–374.

Hiraoka, H., Maruyama, T., Nakamura, Y. *et al.* (1989). A study on modeling of turbulent flows within plant and urban canopies, formalization of turbulence model (in Japanese), *Journal of Architecture, Planning and Environmental Engineering*, **AIJ 406**, 1–9.

Huang, Y.J., Akbari, H., Taha, H. *et al.* (1987). The potential of vegetation in reducing the cooling loads in residential buildings, *Journal of Climate and Applied Meteorology*, **26**, 1103–1116.

Jusuf, S.K., Wong, N.H., Hagen, E. *et al.* (2007). Influence of land use on the urban heat island in Singapore, *Habitat International*, **31**, 232–242.

Kanda, M., Kawai, T. and Nakagawa K. (2005a). Simple theoretical radiation scheme for regular building array, *Boundary-Layer Meteorology*, **114**, 71–90.

Kanda. M., Kawai. T., Kanega. M. *et al.* (2005b). Simple energy balance model for regular building array, *Boundary-Layer Meteorology*, **116**, 423–443.

Knowles, R.L. (1977). *Energy and Form: an Ecological Approach to Urban Growth*, The MIT Press, Cambridge, MA.

Kondo, H., Genchi, Y., Kikegawa, Y. *et al.* (2005). Development of a multi-layer urban canopy model for the analysis of energy consumption in a big city: Structure of the urban canopy model and its basic performance, *Boundary-Layer Meteorology*, **116**, 395–421.

Kondo, H. and Liu, F.-H. (1998). A study on the urban thermal environment obtained through one-dimensional urban canopy model (in Japanese), *Journal of Japan Society for Atmospheric Environment*, **83**, 179–192.

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

Kolokotroni, M., Zhang, Y. and Giridharan, R. (2009). Heating and cooling degree day predictions within the London urban heat island area, *Building Services Engineering Research and Technology*, **30**(3), 183–202.

Kusaka, H., Kondo, H., Kikegawa, Y. *et al.* (2001). A simple single-layer urban canopy model for atmospheric models: comparison with multilayer and slab models, *Boundary-Layer Meteorology*, **101**, 329–358.

Landsberg, H.E. (1981). *The Urban Climate*, Academic Press, New York, NY.

Li, D.H.W., Lam, J.C. (2001). An analysis of climatic parameters and sky condition classification, *Building and Environment*, **36**, 435–445.

Lyle, J.T. (1994). *Regenerative Design for Sustainable Development*, John Wiley & Sons, New York, NY.

Martilli, A., Clappier, A. and Rotach, M.W. (2002). An urban surface exchange parametrization for mesoscale models, *Boundary-Layer Meteorology*, **104**, 261–304.

Martilli, A. (2007). Current research and future challenges in urban mesoscale modelling, *International Journal of Climatology*, **27**, 1909–1918.

Maruyama, T. (1991). Numerical simulation of turbulent boundary layer over complicated surfaces such as urban areas (in Japanese), *Journal of Wind Engineering*, **47**, 81–82.

Masson, V. (2000). A physically-based scheme for the urban energy budget in atmospheric models, *Boundary-Layer Meteorology*, **94**, 357–397.

Mirzaei, P.A. and Haghighat, F. (2010). Approaches to study urban heat island-abilities and limitations, *Building and Environment*, **45**, 2192–2201.

Ng, E. (2012). Towards planning and practical understanding of the need for meteorological and climate information in design of high-density cities: a case study of Hong Kong, *International Journal of Climatology*, **32**, 582–598.

Ng, E., Chen, L., Wang, Y. *et al.* (2012). A study on the cooling effects of greening in high-density: an experience from Hong Kong, *Building and Environment*, **47**, 256–271.

Nichol, J. and Wong, M.S. (2005). Modelling urban environment quality in a tropical city, *Landscape and Urban Planning*, **73**, 49–58.

Nieuwolt, S. (1986). "Design for climate in hot, humid cities", in Oke, T.R. (ed.), *Urban Climatology and its Applications with Special Regard to Tropical Areas*, proceedings of the technical conference organised by the world Meteorological Organisation, WMO-652, Geneva, Switzerland.

Oke, T.R. (1987). *Boundary Layer Climate*, Methuen, London, UK.

Oke, T.R. (1988). The urban energy balance, *Progress in Physical Geography*, **12**, 471–508.

Oke, T.R., Taesler, R. and Olsson, L.E. (1990–91). The tropical climate experiment (TRUCE), *Energy and Building*, **15**(1–2), 67–73.

Ooka, R., Harayama, K., Murakami, S. *et al.* (2004). "Study on urban heat islands in Tokyo metropolitan area using a meteorological mesoscale model incorporating an urban canopy model", in proceedings of the Fifth Symposium on the Urban Environment, 23–26 August 2004, Vancouver, BC.

Ooka, R. (2007). Recent development of assessment tools for urban climate and heat-island investigation especially based on experience in Japan, *International Journal of Climatology*, **27**, 1919–1930.

Park, H.S. (1987). City size and urban heat island intensity for Japanese and Korean cities, *Geographical review of Japan,* **60**, 238–250.

Rasheed, A., Robinson, D., Clappier, A. *et al.* (2011). Representing complex urban geometries in mesoscale modelling, *International Journal of Climatology*, **31**, 289–301.

Roth, M. (2007). Review of urban climate research in (sub) tropical regions, *International Journal of Climatology*, **27**, 1859–1873.

Runnals, K.E. and Oke, T.R. (2000). Dynamics and controls of the near-surface heat island of Vancouver, British Columbia, *Physical Geography*, **21**, 283–304.

Sakakibara, Y. (1995). A numerical study of the effect of urban geometry upon the surface energy budget, *Atmospheric Environment*, **30**, 487–496.

Santamouris, M. (ed.). (2001). *Energy and Climate in the Urban Built Environment*, James & James, London, UK.

Sham, S. (1990–91). Urban climatology in Malaysia: an overview, *Energy and Buildings*, **15**(1–2), 105–117.

Shashua-Bar, L. and Hoffman, M.E. (2003). Geometry and orientation aspects in passive cooling of canyon streets with trees, *Energy and Buildings*, **35**, 61–80.

Shashua-Bar, L., Hoffman, M.E. and Tzamir, Y. (2006). Integrated thermal effects of generic built forms and vegetation on the UCL microclimate, *Building and Environment*, **41**, 343–354.

Stone, B. and Rodgers (Jr.), M.O. (2001). Urban form and thermal efficiency, *Journal of American Planning Association,* **67**(2), 186–198.

Sundersingh, S.D. (1990–91). Effect of heat islands over urban madras and measures for its mitigation, *Energy and Buildings*, **15–16**, 245–252.

Swaid, H. and Hoffman, M.E. (1990). Prediction of urban air temperature variations using analytical CTTC model, *Energy and buildings*, **14**(4), 313–324.

Taesler, R. (1986). "Urban climatological methods and data", in Oke, T.R. (ed.), *Urban Climatology and its Applications with Special Regard to Tropical Areas*, proceedings of the technical conference organised by the world Meteorological Organisation, WMO-652, Geneva, Switzerland.

Tso, C.P. (1996). A survey of urban heat island studies in two tropical cities, *Atmospheric Environment*, **30**(3), 507–519.

Vu Thanh, C.A., Ashie, Y. and Asaeda, T. (2000). Development of the urban climate simulation system for urban and architectural planning. Part 1, Turbulence modeling of urban atmospheric boundary layer (in Japanese), *Journal of Architecture, Planning and Environmental Engineering*, **AIJ 536**, 95–99.

Vu Thanh, C.A., Ashie, Y. and Asaeda, T. (2002). A k–ε turbulence closure model for the atmospheric boundary layer including urban canopy, *Boundary-Layer Meteorology*, **102**, 459–490.

Watkins, R., Palmer, J., Kolokotroni, M. *et al.* (2002). The balance of the annual heating and cooling demand within the London urban heat island, *Building Services and Engineering Research and Technology*, **23**(4), 207–213.

Wong, N.H., Jusuf, S.K., Syafii, N.I. *et al.* (2011). Evaluation of the impact of the surrounding urban morphology on building energy consumption, *Solar Energy*, **85**, 57–71.

Yamada, T. and Bunker, S. (1988). Development of a nested grid, second moment turbulence closure model and application to the 1982 ASCOT Brush Creek data simulation, *Journal of Applied Meteorology*, **27**, 562–578.

Yang, F., Lau, S.S.Y. and 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**, 115–134.

Yang, F., Lau, S.S.Y. and Qian, F. (2011). Urban design to lower summertime outdoor temperature: an empirical study on high- rise housing in Shanghai, *Building and Environment*, **46**, 769–785.

Chapter 9

Urban exemplars of climate-sensitive design

Patricia Drach

It is rare to find built examples of exemplary climate-sensitive design approaches at large enough scales to make a significant dent in the urban overheating problem in the tropics. However, lessons could be learnt from street- and neigborhood-scale approaches and design solutions. This chapter presents exemplary approaches and explores lessons from these approaches for larger-scale applications. The examples presented are from Asia and South America.

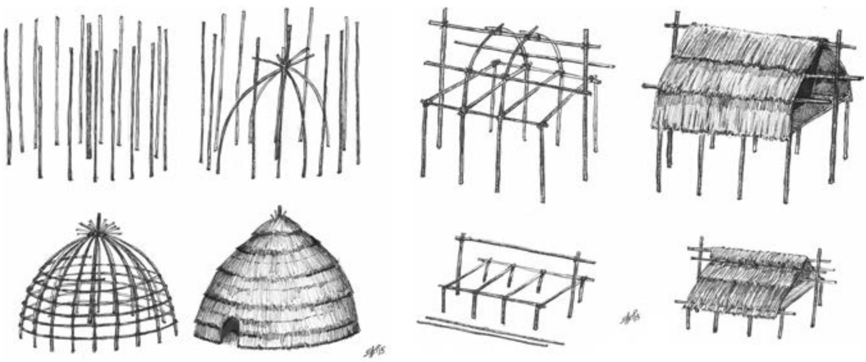
9.1 Traditional Exemplars

The urban phenomenon can be characterized, among other things, by its extreme complexity. While this has been the case from the beginning, the industrial revolution introduced additional tension between science and tradition. However, the greatest change in urban design came a little later, with the social, economic and technical changes that occurred after the Second World War. The increasing technological development enabled the creation of 'climatized' spaces with artificial lighting, which freed buildings from a strong dependence on the environment. From that moment on, irrespective of the region, climate or available levels of lighting, it became possible to build in a minimalist, almost 'ascetic' way, isolating and distancing the 'shelter' from its surroundings and, therefore, from social and cultural interference.

These technological advances, which at first seemed to be exclusively positive, allowed for the detachment of man from his surroundings, generating a kind of democratization of dwelling. However, now that the initial excitement brought about by a false sense of freedom to design has worn out, we find ourselves trying to deal with the waste left by the 'keg party'.

The transference of architectural typologies to colonized tropical cities has often resulted in distancing the ideal locus due to the loss of its perception and identity. The locus here is understood in its broadest sense, i.e. its environmental and climatic conditions are taken into account together with its cultural, historical and technological aspects (Romero, 2001). The spirit of the locus is present in it, the genius loci, that ancient cultures were able to capture (Romero, 2001).

The original homes of these countries were in tune with the local climate characteristics and could therefore be considered as 'climate-sensitive design.' Figure 9.1a shows the building stages of a traditional Xavante house (two types of Waiãpi houses). Waiãpi is the name of an indigenous people in the north of South America. The houses differ only in regards to the stilts, which are placed 1.5 m



(a) (b)

Figure 9.1. (a) Xavante house. Design: Maria Carolina Young Rodrigues and (b) two types of Waiãpi houses. (Source: (a) and (b) photographs produced for this chapter by Eduardo Roxo Pereira)

or 2 m above the ground: house on stilts (*iura*) and ground house (ywy'o) (Fig. 9.1b).

The same seems to have occurred during early colonial times in Latin America, Asia and Africa, where the buildings of the early occupants were sensitive to the design developed for the place. It was imperative to be consistent with the environment since they could not rely on artificial means of acclimatization and lighting. In the process of the colonization of South America, the building of towns and villages was strongly influenced by the Portuguese colonizers in Brazil, and the Spanish in the rest of the American continent. Their architecture and urbanism concepts have undergone some adjustments to the tropical climate, but many elements brought by the colonial architecture suited the tropical climate perfectly, probably because of the earlier Moorish influence on these two regions of the Iberian Peninsula. Issues such as ventilation and shading were addressed by the use of lattice or wooden crates (Fig. 9.2a). Despite the diversity of materials available, the use of water, inner courtyards, balconies (Fig. 9.2b) and lattice was incorporated to the architecture in the tropics.

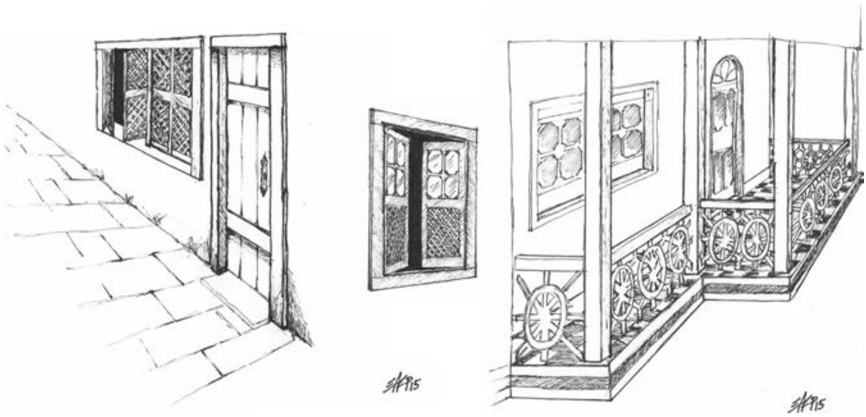


Figure 9.2. (a) Fences and trellis screens allow for ventilation and lighting without reducing privacy and (b) balconies. (Source: (a) and (b) photographs produced for this chapter by Eduardo Roxo Pereira)

9.2 Current Approaches — Dense and Compact Cities and the Tropics

Despite the criticism regarding large urban sprawl — with its suburbs and dormitory towns occupied only during the day — it remains quite attractive in the tropics and is often fostered by public policies, since it promises 'safe' and less polluted living environments far from the urban chaos.

However, a totally opposite model — the compact city — is being proposed and used, mainly in Europe. According to Girardet (2007), this model is based on concentration, connectivity and multifunctionality. The compact city is smaller in dimension and has an intermediate density. This model, presented as a sustainable alternative, has been widely championed in recent years, including by Richard Rogers and Girardet (Rogers and Gumuchdjian, 2000). Rogers (1998) considers that the 'densification' of a city can bring environmental benefits, since a compact city is dense and socially diverse, where economic and social activities overlap.

Urban densification may represent an attempt to soften the urban and environmental problems caused by the macro scale, but at the same time, it causes new problems such as the verticalization of cities, which impairs ventilation and natural lighting and increases the concentration of air pollution. Another important issue in relation to the high population concentrations in Latin America and Asia is the capacity of local river basins. While large and sprawling cities bring large problems, densification of cities does not guarantee sustainability, although it must be understood as an attempt to avoid environmental problems.

From the bioclimatic point of view, and in particular in the humid tropics, the compact city promotes the increase of air temperature in the urban environment, contributing to the formation of heat islands, and, consequently, increasing pollution and consumption of electricity for air conditioning. This often occurs due to speculation, which replaces buildings that are still in living conditions with more profitable ones. The increase of human concentration might lead to fewer vehicles but the speed of the remaining vehicles decreases, leading to greater burning of fossil fuels, which leads to a concentration of air pollutants, hence the recognition that the urban form and urban morphology interfere on the heat exchange, ventilation and concentration of pollutants in urban areas (Drach *et al.*, 2014; Barbosa *et al.*, 2010a, 2010b).

There are many variables and possibilities for urban form and no proposition should consider solutions guided solely by ideologies or generalizations. Simulation exercises can assist the decision-making process of architects and planners. The results of computer simulations confirm that the issues related to compact cities are still open, showing some advantages to urban sprawl, especially in warm climates.

Barbosa *et al.* (2010a) compared three degrees of densities in a simulational study in Camboinhas District, Niterói, Brazil: sprawl, intermediate and dense area. The differences in temperature that were observed by the simulations were around 2°C from sprawl to intermediate, and from intermediate to dense occupation.

Camboinhas was designed to be a sprawling residential neighborhood where most of the buildings have two floors and are separated by green areas (Figs. 9.3a–9.3c). The region has shown an intense occupation, caused in part by the expansion of the city of Niterói towards the coast. The proximity to the city center and the beauty of the natural landscape can be considered as the main elements that contributed to the occupation of this area.

The densification process proposed in the study changed the region in two stages: in the intermediate scenario, besides the introduction of new buildings, the height of buildings was elevated. Figure 9.4 shows (a) the current occupation of the city, (b) intermediate occupation and (c) a proposal for a sharp densification.

Figure 9.5 shows the results of an ENVI-met (Bruse, 2010a, 2010b) simulation for 21 January 2010, a typical summer day, and therefore possibly with a high degree of discomfort. For all experiments in the study, vegetation was simulated as a dense grass without taking into consideration trees or shrubs.

Column 1 shows the increase in temperature as the density increased. In the sprawling neighborhood, which represents the

Figure 9.3. Camboinhas neighborhood, Niterói, Brazil. (Source: Barbosa *et al.*, 2010b)

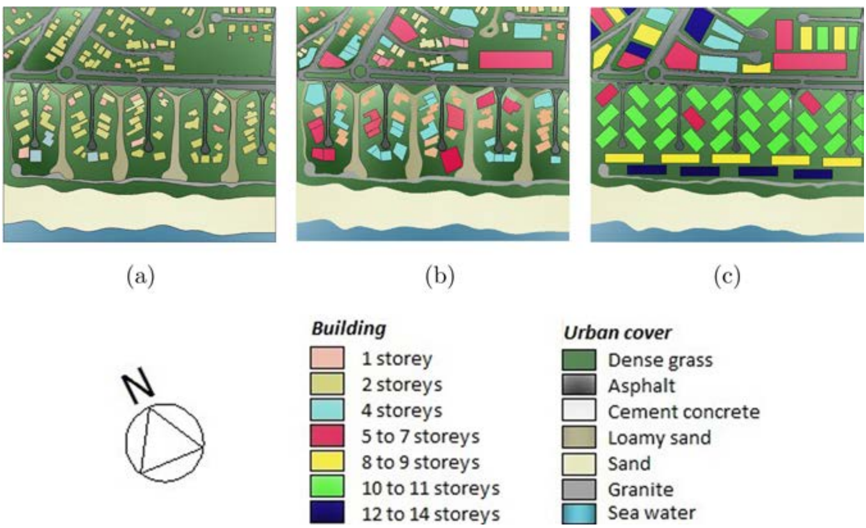


Figure 9.4. Density experiments: (a) sprawl, (b) intermediate and (c) dense areas. (Source: Barbosa *et al.*, 2010b)

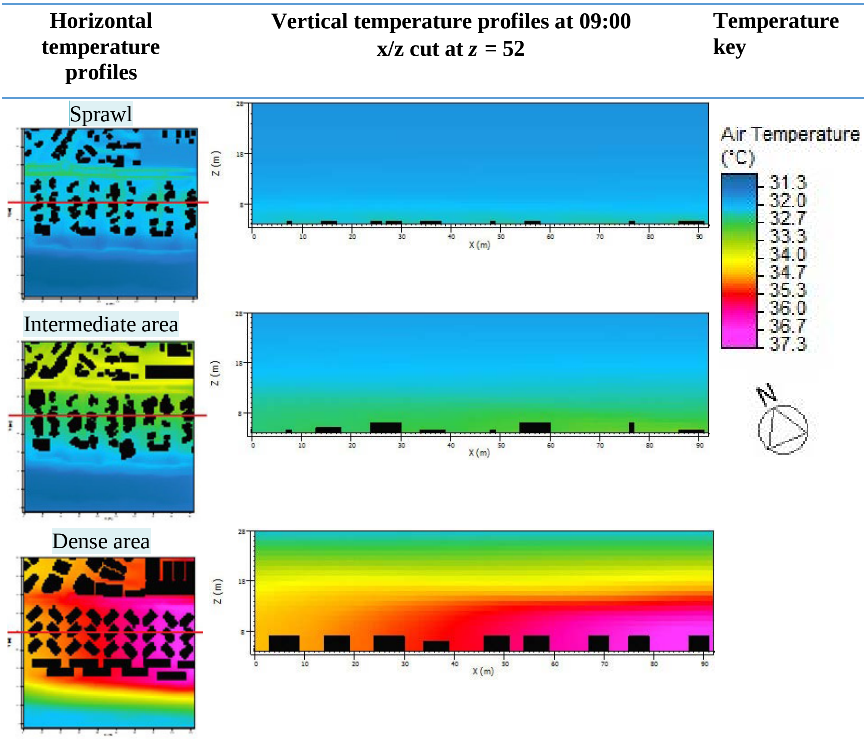


Figure 9.5. Horizontal and vertical temperature across the three density situations studied. (Source: Barbosa *et al.*, 2010b)

current status of Camboinhas, the highest temperatures are distributed along asphalt-paved areas. The same applies to the intermediate neighborhood. In the dense scenario a considerable increase in temperature is seen, indicating possible formation of heat islands (an increase in potential temperature of up to 4°C). Regardless of the quantitative values, the fact that the three situations have had the same initial and boundary conditions allows for a qualitative analysis.

It should be noted that densification in this study did not result in the increase of paved areas with asphalt or stone, which would probably further increase the temperature. Thus, the effects are purely due to changes in building density and point to the advantages and disadvantages of compact cities in the tropics.

Similar findings were reported by Lombardo (1985) in São Paulo, Brazil that showed horizontal temperature gradients of up to 10°C, although the largest temperature variation between country and town was around 5°C. These studies together with Corbella and Yannas (2003) and Romero (2001) provide strong indication of the need to contextualize densification approaches to suit different climates.

The rapid urbanization in the tropics has not allowed for integrated planning to mitigate the damages caused by intense and disorderly urbanity. In this regard, perhaps the encouragement of small and medium-sized cities could combine the advantages of living in compact cities *sans* the problems caused by megacities. If properly designed, a smaller city can be socially diverse and have different economic activities. This could facilitate better social integration and promote better participation of its members in decision making with respect to urban governance (Moore, 1998).

9.3 Street- and Neigborhood-Scale Approaches

Irrespective of the size of cities, approaches related to street- or neigborhood-scale may represent quality gains for open spaces. Among the strategies for tropical areas, Emmanuel (2005) lists the need to work in small areas in order to achieve better conditions and more comfort in each block of the city. He proposes the use of natural materials (vegetation and water) as cooling agents. In his research, he establishes that microscale actions can affect the microclimate positively, and shows that a large number of small green areas or parks can be more efficient as cooling agents than green areas in the surroundings of a city, a view supported by Chapter 5 as well as Oliveira *et al.* (2011). Emmanuel (2005) also states that elements of greatest climate change potential in a specific area have low efficiency if they are not considered within the micro scale. The influence of green infrastructure on the neighboring environment depends upon the climatic and urban characteristics of the city (Oliveira *et al.*, 2011), necessitating further studies considering the specific characteristics of each city.

9.3.1 *Design strategies — Evidence from the field*

How do we minimize the effects of urban overheating? Urban morphology and vegetation could be pointed out as helpful levers to improve local comfort. Green infrastructure improvement allows for specific action not only in large cities, but also in medium and small cities. The use of vegetation as an ally in the pursuit of a climate-sensitive urbanism has additional benefits, including the provision of ecological niches protected by shade and cooler temperatures, which further increases people's sense of well-being.

Computational simulation

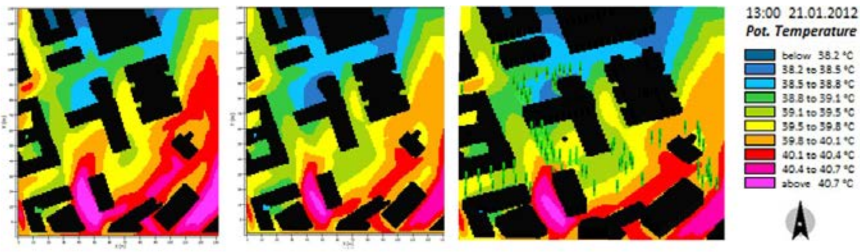
The city center of Rio de Janeiro is an area of intense daily pedestrian traffic promoting its importance as an economic and financial center. Tentative interventions can be observed and their timid initial results seem to be amplified in other parts of the city. Computer simulations for the city center (Drach, 2012) indicate that the introduction of vegetation resulted in air temperature reduction even in areas nearby the vegetation.

An example of such green intervention could the courtyard around the Capanema Palace (formerly the Ministry of Education and Health building, Fig. 9.6). Le Corbusier acted as the project consultant for this building which was jointly developed in 1936 by the architects Lúcio Costa, Carlos Leão, Oscar Niemeyer, Affonso Eduardo Reidy, Ernani Vasconcellos and Jorge Machado Moreira. It is an icon of modernism in Brazil and, more specifically, in Rio de Janeiro.

Figure 9.7 show the likely air temperature effect of introducing few carefully placed trees. Areas of the highest temperature (>40.1°C) are substantially reduced.

Figure 9.8 shows the temperature profile at a receptor point (black dot in Fig. 9.7c). It is near the trees but not under them, thus allowing for the estimation of indirect temperature effect. The differences between the temperatures can be almost 1°C, even when not directly in the tree shade. The rate of temperature change (Fig. 9.8b) shows these differences become more accentuated after 8 a.m., reaching nearly 1°C.

Figure 9.6. Courtyard around the Capanema Palace. (Source: Photograph by Rafael Ramilos Braga)

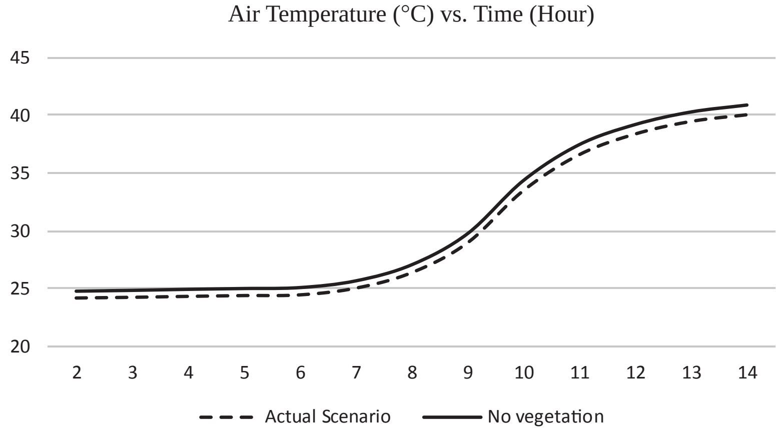


(a) (b) (c) (d)

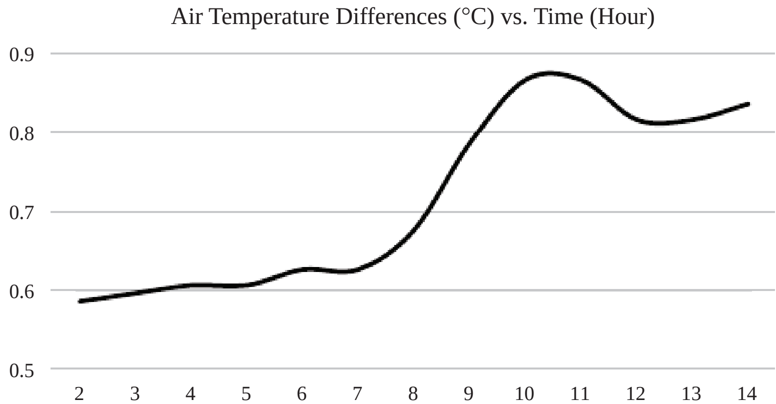
Figure 9.7. Effect of vegetation on local temperature: (a) no vegetation, (b) vegetation (plan view), (c) vegetation (3D view). (Source: Drach, 2012)

Thermal comfort survey

Such theoretical findings are also matched by a thermal comfort survey. Drach (2012) reported a thermal comfort survey conducted in the pedestrianized central area of Rio de Janeiro, representing a wide variety of urban formations (narrow streets, neighborhood green spaces, urban parks, uniform and non-uniform street canyons and



(a)



(b)

Figure 9.8. Temperature effect of introducing trees: (a) temperature profile and (b) rate of change. (Source: Drach, 2012)

public squares). Figure 9.9 shows two measurement locations: one corresponds to a tree-lined street (Fig. 9.9a) whereas the other consists of an area with limited vegetation (Fig. 9.9b). In the latter, no shelter is available to passersby. A comfort questionnaire — personalized according to the recommendations of ISO 10551 (1995) — was used for assessing the respondents' thermal perception. All respondents were volunteers necessarily living in the greater Rio de Janeiro

(a) (b)

Figure 9.9. Views of measurement sites in the city center of Rio de Janeiro (a) tree-lined street and (b) street devoid of vegetation. (Source: Photographs by Henrique Drach)

area for more than 6 months, and had been outdoors for at least 15 minutes prior to the survey. Thermal sensation was recorded on a 7-point two-pole scale ranging from −3 (cold), over 0 (neutral), to +3 (hot), where 'neutral' represents an equal comfort state.

Figure 9.10 shows a thermal sensation comparison between the two sites. Over 50% more respondents reported a neutral thermal sensation (69% for tree-lined street and 18% for no tree street). This reinforces the understanding that simple interventions are often able to cause significant changes in the perception of spaces by their users.

9.4 Larger-Scale Applications — Asia

Although the large-scale approaches, in general, prioritize the question of sustainability, it is possible to identify aspects in common

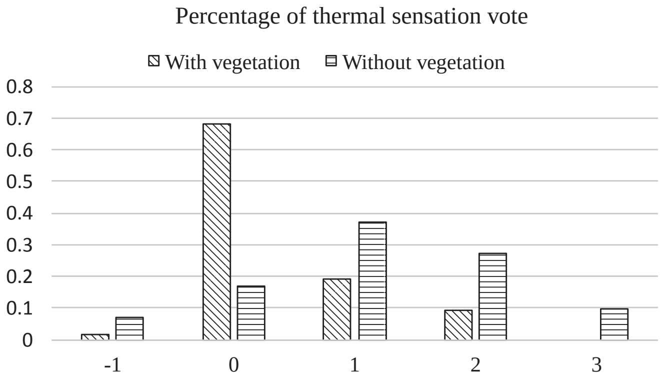


Figure 9.10. Comparison of thermal sensation between the tree-lined and no-tree sites in Rio de Janeiro. (Source: Patricia Drach, 2014)

with the climate-sensitive design. This is the case with Masdar city, a project designed by Norman Foster and located close to Abu Dhabi, capital of the United Arab Emirates. While the focus of the new city is on energy sustainability, lack of water is a major sustainability challenge. However, the design incorporates features of a climate-sensitive design, which allows for the inclusion of aspects of the Arab vernacular architecture interpreted with cutting-edge technology.

The project plan and design of Masdar shows the overall distribution of the city in two squares which are connected by a 'via park'. The city and its urban grid were oriented diagonally in relation to the coast (southeast-northwest direction) in order to allow for better permeation of night breezes in Masdar. The typology of buildings and the use of photovoltaic panels on roofs assist in the shading of buildings and roads, thus minimizing thermal sensation.

Streets are narrow and the angular disposition of the buildings helps create shadow areas. Side streets present elements of light and shadow transition, linking the 'in' and the 'out' (example, Masdar Institute of Science and Technology: Research Center for alternative energy and sustainability).

The muxarabis — elements of vernacular Arab architecture — can be observed in the inner courtyard of the Masdar Institute of Science and Technology.

Given the intense heat ventilation, light and view in the Middle East could not be associated with a single window at the same time because each function demands a different window configuration (Fathy, 1986). The wind-catch, malqaf, was created to improve ventilation requirements. It catches wind from high above — where the air is cooler, stronger and with less sand and other particles — and channels it down into the building. Masdar city design has redesigned wind towers and placed them in different areas of the city.

Thus, technology can be considered as the highlight in the development of the city. It is, in fact, a large laboratory, which is mainly concerned with environmental technologies and the use of clean energy (Barbosa, 2013).

9.5 Larger-Scale Applications — South America

Having undergone strong urban growth relatively early in the last century, many countries in South America are going through a process of urban revitalization. This form of 'rescue' of spaces that were lost either by disuse or by clandestine occupations has presented important results regarding new occupation of urban areas, and consequent reduction of violence and other social ills. Social issues have been the focus of such interventions in Colombia, Argentina, Peru, Chile and Brazil. This is opposed to large enterprises that focus on sustainability and energy efficiency labels. They prioritize the efficient management of the use of energy and water. Generating their own energy is not yet their focus.

An example of a large-scale intervention is presented in Colombia, where Bogotá, its capital city, and Medellin suffered an intense process of urban regeneration. Medellin in particular has addressed the issue of urban mobility in an original way with the implementation of a metro-cable system. This system allows poor communities access to areas that are difficult to reach on account of steep slopes of hills in the outskirts of the city (Vescina, 2010). The metro-cable passes through different neighborhoods, which enhances accessibility and allows for the emergence of new urban spaces.

In this model, the public transport system acts as the mainspring of urban transformation (Ghione, 2014), given its power of social

(a) (b) (c)

Figure 9.11. (a) Metro-cable in Medellin city, Colombia, (b) escalator system in San Javier Community and (c) detail of the escalator system. (Source: Photographs by Roberto Ghione)

transformation. In addition to public transport, the original urban accessibility system includes an integrated system of cycle paths and even escalators to San Javier Community in Medellin (Fig. 9.11).

According to Vescina (2010), the urban revitalization process in Medellin has made explicit the most efficient and appropriate infrastructure in this urban landscape, creating an immediate visual impact. This is in contrast to other interventions, where the usual practice is to hide such infrastructure.

However, the revitalization processes in Latin America must be viewed with caution since, in many cases, they serve the interests of real estate investors, and end up presenting important antagonisms in some areas of cities. The development of large urban projects seems to be constant in Latin America. Sequera and Mateos (2014) indicate the partnership between the public and private sectors as one of the most significant issues that contribute to this situation, which has become widespread and has tilted many of the urban interventions towards real estate market interests.

In Puerto Madero, Argentina, Sequera and Mateos (2014) indicate that the revitalization of the ancient port of Buenos Aires, Argentina, resulted in an "archipelago of privileges and privileged". They also

(a)

(b)

Figure 9.12. Puerto Madero, Buenos Aires, Argentina: (a) overview and (b) Puente de la Mujer. (Source: Municipalidad de Buenos Aires — Historia de los Barrios.http://www.buenosaires.gob.ar/)

indicate that the strategies adopted in this region have changed the space into something else, i.e. the physical space remains, but the history and local culture are lost in the process of change. Figure 9.12 shows images of Puerto Madero neighborhood and Río de la Plata. The Puente de la Mujer (Woman's Bridge) was designed by the Spanish architect Santiago Calatrava.

While the beauty of the 'new neighborhood' can be easily observed, the region "as opposed to the characteristics of adjacent neighborhoods is an island of order and security" (Sequera and

Mateos, 2014), resulting from what is termed as a 'new business paradigm' or urban entrepreneurship.

According to Tella (2010), the lack of social housing schemes in Puerto Madero expresses the intention that the project remains without diversity and segregated from the city. This situation remains despite the existing demand of different social classes for housing in Buenos Aires. Tella points out that "part of the huge surplus income generated by the operation has never been directed to the improvement of other areas, such as the ones in the south of the city", even in the face of an accelerated growth process of informal settlements in Buenos Aires.

A similar process of change is taking place in the port region of Rio de Janeiro, Brazil. Rabha (2004) points out that this harbor area was associated with slavery and poverty during the 19$^{\text{th}}$ and 20$^{\text{th}}$ centuries, and consequently, connected with the presence of disease and danger, where unsanitary and illegal activities flourished. The port neighborhoods were

> . . .also chosen locations for complex uses, such as the first city cemetery (the British Cemetery, in 1809), the hospital for isolation of patients with infectious diseases (1853), warehouses and depots, or to protect the African cultural tradition, with its free exercise restricted to a few places in the city. The danger and bad reputation were linked to the work at the port region, labeling its people and the place. (Rabha, 2004).

The modifications carried out in the city of Rio de Janeiro in early 20$^{\text{th}}$ century revitalized the region, promoting changes not only in the appearance of the city but also the port infrastructure, through its modernization. New changes occurred in the 1960s, but this time, they affected the port operations negatively, which led to the deterioration of the port region, and resulted in the deactivation of several sheds and warehouses (Leal, 2010). Once again, the region faced "danger, violence and bad name".

Figure 9.13 shows the project Porto Maravilha (Port Marvelous) — still in its implementation phase — that brings about controversial opinions as it pits commercial interests that permeate the project against real benefits for local people and places. Initial moves indicate an increase in property values, which may be the

(a)

(b)

Figure 9.13. Porto Maravilha: (a) overview of Praça Mauá and (b) Museum of Tomorrow (designed by Santiago Calatrava). (Source: CDURP — Rio de Janeiro port region urban development company — http://portomaravilha.com.br/test/project.aspx)

result of the improvements caused by investments or a consequence of speculation. The beginning of a gentrification process and eviction of locals has begun (Leal, 2010) and this process of exclusion of local diversity seems to be very similar to the one in Puerto Madero.

Thus, the regeneration processes of both Puerto Madero in Buenos Aires, and Porto Maravilha in Rio de Janeiro take into account the financial speculation as regards the real estate market but the gains brought about by urban renewal in terms of security and functionality are not associated with the permanence of the original population. There is a gentrification process that leads to the absence of social, economic and cultural diversity. Additionally, the issue of mobility in the case of Porto Maravilha keeps repeating the current paradigms of urban mobility, focusing on the movement of vehicles and not of people.

9.5.1 *Large-scale climate-sensitive design in Latin America*

The approaches to large-scale climate-sensitive design still seem far-fetched in Latin America. However, one example of such an approach that is worthy of mention is the Sarah Kubitschek Network of Hospitals designed by the Brazilian architect João Figueiras Lima da Gama, known as Lelé (1932–2014).[1]

His experience as a young architect involved with the construction of Brasília, the capital city of Brazil, as Lúcio Costa and Oscar Niemeyer's pupil was the starting point of his future research in prefabrication and industrialization in the construction process.

In 1963, Lelé and his wife Alda Rabello Cunha, also an architect, suffered a car accident that left them hospitalized for two months in Brasília. According to Lelé (2004), during this time they first met with Dr. Aloysio Campos da Paz Jr., the director of the orthopedic service in the hospital. The humanistic approach of Campos da Paz Jr. allowed for the establishment of a connection between them, which later developed into a professional partnership for the creation of the Sarah Kubitschek Network of Hospitals (Lima, 2004).

All the units belonging to the Sarah Network — as the Sarah Kubitschek Network of Hospitals is known — are characterized by the careful integration of its architectural and urban design through a climate-sensitive design approach, which takes into consideration the needs of the hospital program. The hospitals are located in the southern, southeastern, central, northeast and north regions of Brazil, and each unit is suitable for different regional climates.

In the process of expanding the Sarah Network, the principles that should be used as guidelines for the construction of new buildings for

[1] At the age of 25, Lelé became Lúcio Costa and Oscar Niemeyer's pupil when they were developing the project to create Brasília, the capital city of Brazil. His work constantly prioritized climate, vegetation and local topography.

(a)

(b)

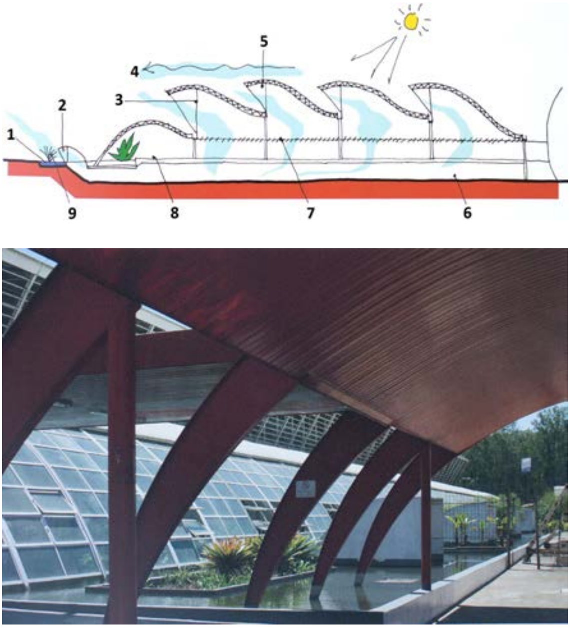
Figure 9.14. Sarah Network unit — Salvador, BA: (a) Clinic waiting room and (b) passageways. (Source: Photographs by Nelson Kon)

the network were established. These guidelines included, for example, standardization of building elements through a process of industrialization and the use of natural elements as allies in creating comfortable spaces (Lima, 2009). The design of indoor and outdoor spaces carefully considers the use of colors, the dimension of rooms and spaces, which appear integrated with large gardens and water features, lighting and natural ventilation. These factors are extremely important, especially when we consider the challenge involved in using natural ventilation strategies to achieve thermal comfort in a tropical country such as Brazil.

Figure 9.14 shows the Sarah Network unit in Salvador, Bahia, where the clinic waiting room and passageways are integrated with vegetation, protected from the sun but completely open to the outside (providing an example of the linking of the 'in' and the 'out' as discussed in Chapter 2).

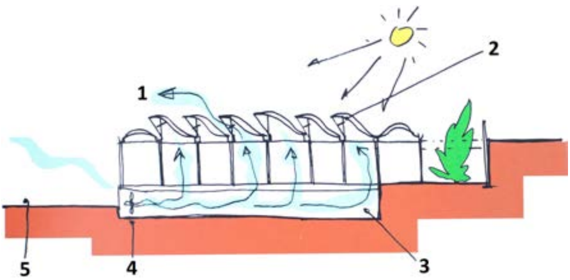
Underground galleries to facilitate hospital audit and maintenance of water, sewer, gas, electrical installations and others can be found in the Sarah Network hospitals. These galleries are used for capturing wind, which is brought to the internal spaces naturally or with the help of blower fans associated with water sprinklers where required.

The way the wind is captured and sent to the internal areas of the buildings depends on the location of the project and the impact of prevailing winds. In the city of São Carlos in São Paulo, for example, low humidity prevails almost throughout the year. Therefore,



Sarah Network — General Hospital, São Carlos, SP
1 Reflection pool
2 Air capture
3 Glass
4 Prevailing winds
5 Ventilation opening
6 Pipe gallery
7 Tilting windows (ventilation control)
8 Waiting room
9 Water sprinkler

(a)



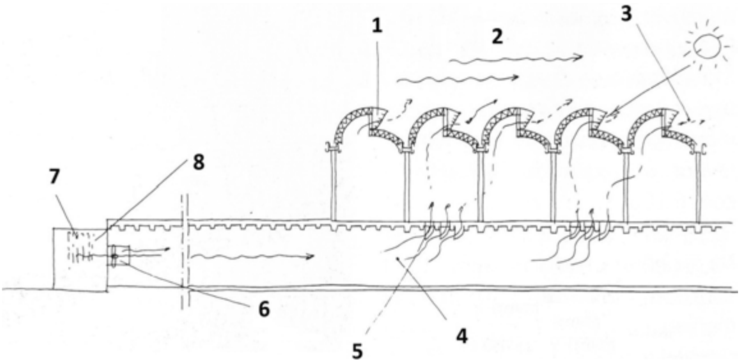
Sarah Network — General Hospital, São Carlos, SP
1 Prevailing winds
2 Tilting windows (ventilation control)
3 Pipe gallery
4 Fan for pushing air
5 Patio

(b)

Figure 9.15. Ventilation system in Sarah Network in São Carlos, SP: (a) natural and (b) forced ventilation with the aid of a fan. (Source: (a) photographs by "Lelé" and Silvana Romano Santos respectively and (b) photograph by "Lelé")

humidification associated with ventilation is the most appropriate strategy.

Figure 9.15a presents the natural ventilation system, where air capture occurs at the water surface and a water spray helps to



Sarah Network — Natal, RN
1 Sheds
2 Prevailing winds
3 Hot air extraction
4 Pipe gallery
5 Air entrance
6 Exhaust system
7 Water sprinklers
8 Air capture

Figure 9.16. Ventilation system of water sprinklers associated with an exhaust system, Sarah Network in Natal, RN. (Source: Photograph by "Lelé")

humidify the air. Where water was not available (Fig. 9.15b) the choice was to use forced ventilation with a fan, forcing the air into the pipe gallery.

The Sarah Network hospital in Natal, Rio Grande do Norte State (Fig. 9.16) uses a ventilation system with water sprinklers on an exhaust system that sucks well-moistened air. The system pushes the air through the pipe galleries with cold air entering the building from below. Openings in the sheds face opposite direction to the prevailing winds.

The community lounge in the Sarah Network unit located in São Luís, state of Maranhão, located in the northern region of Brazil (Lima, 2012), shows the integration of inner spaces with the outside via the use of local vegetation and shaded areas, allowing for the perfect integration between the two (Fig. 9.17). The side view allows us to observe the dynamics of airflow with the use of sheds.

It is important to point out that the Sarah Network hospital in Salvador can be regarded as the starting point of the development of the Sarah Network Technological Center (Centro de Tecnologia da Rede Sarah — CTRS). It was founded in 1991 in the city of

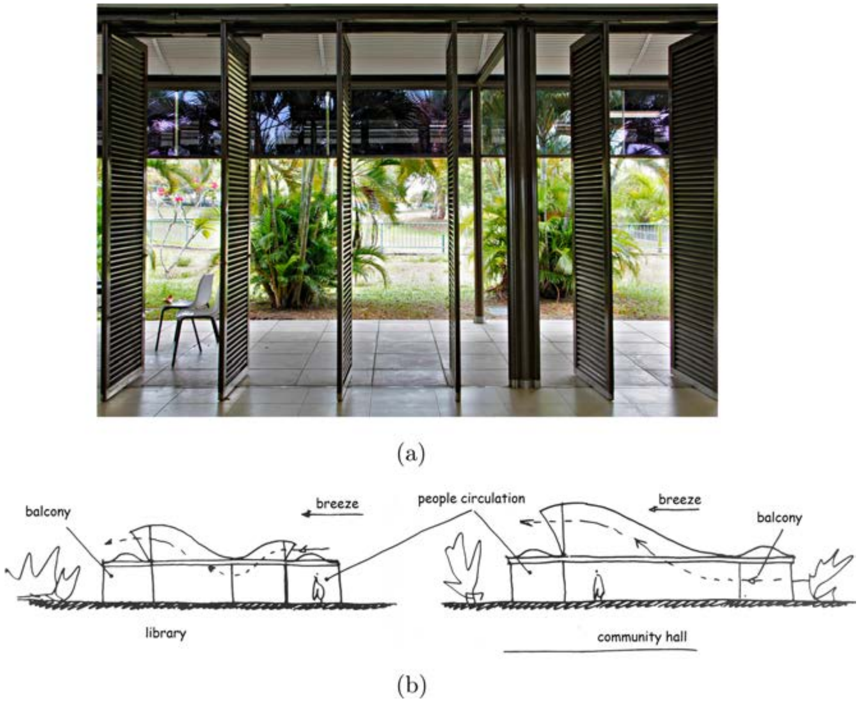
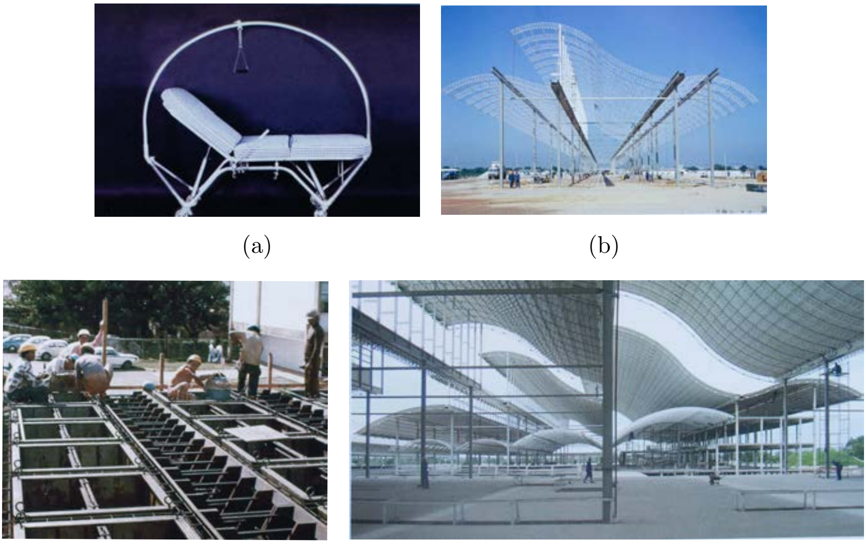


Figure 9.17. Sarah Network unit — São Luís, MA: (a) Veranda in the community lounge and (b) side view sketches. (Source: Photograph by Francisco Otoni)

Salvador, Bahia. Lelé devised various workshops involving a variety of materials such as wood, metal, cement and plastic, among others, which are part of the CTRS. This truly off-site construction approach is dedicated to the maintenance and development of building blocks for the hospitals as well as the creation of new hospital equipment (Fig. 9.18).

The application of the principles and guidelines mentioned before, i.e., the standardization of building elements through a process of industrialization and the use of natural elements as allies in creating comfort spaces (Lima, 2009), brings economy and speed to the process of construction. It also represents a considerable reduction in running costs (Lima, 2009). Figure 9.19 shows a sketch and two different phases of the construction of the Sarah Network unit in Brasília, DF. The structural skeleton is covered by pre-molded



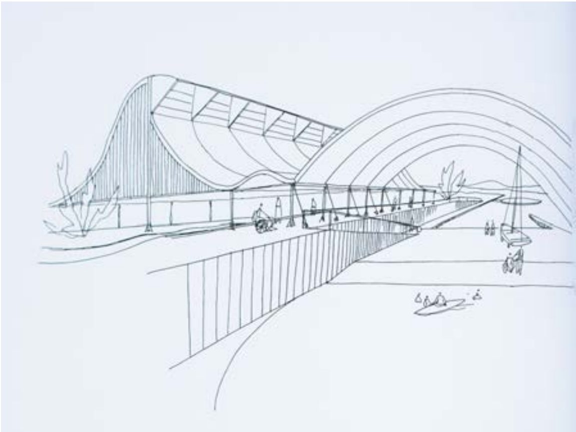
(a) (b) (c) (d)

Figure 9.18. (a) Hospital equipment, (b, c) structures and (d) pre-molded blocks. (Source: Photographs by "Lelé")

blocks where the shed allows for ventilation and daylighting of the inner spaces. The presence of a reflection pool fulfills an essential need in this extremely dry region.

The integration of hydrotherapy areas as climatizing elements in different climates can be seen in Fig. 9.20 (a–b: Rio de Janeiro; c–d: Brasília). The structure of the sheds is always present.

The Sarah Network unit located in Salvador, BA, apart from being a Brazilian exemplar of the use of technology in an industrialized process of construction, has been conceived based on climate-sensitive design techniques such as sun protection, integration with vegetation, humidification, use of natural light and an intelligent system of ventilation using the little breeze available. The green areas near the buildings help to minimize heat gains in the internal space and offer shade to the building as a whole. The careful planning of outdoor areas includes reflection pools, which help create areas of comfort in the building's surroundings. Long axis along the east-west, use of colors outdoors and indoors (Figs. 9.21a and 9.21b),



(a)

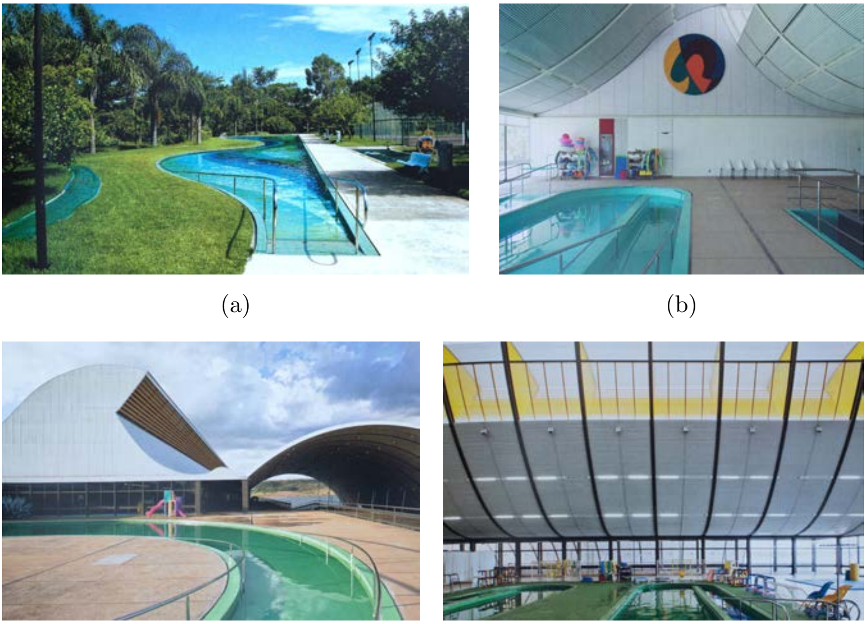
(b)

(c)

Figure 9.19. Sarah Network unit in Brasília, DF: (a) sketch, (b) structure (c) the structure covered by pre-molded blocks. (Source: (a) and (b) photographs by "Lelé" and (c) photograph by Nelson Kon)

natural lighting in the indoor hallways together with operable windows to control indoor ventilation (Fig. 9.21c) and a reflecting pool for patients (Fig. 9.21d) that moistens the air are additional features that aid the climate sensitivity of this building.

The efficient ventilation system developed by the project ensures that, even in a tropical region, the air-conditioning system be used only in some special areas such as operating theaters, computer centers, x-ray rooms, necropsy room and others where low temperatures are required.



(a) (b)

(c) (d)

Figure 9.20. Hydrotherapy areas: indoor and outdoor areas in (a–b) Rio de Janeiro and (c–d) Brasília. (Source: (a) and (b) photographs by "Lelé"; (c) and (d) photographs by Nelson Kon)

Thus, the Sarah Network designed by architect Lelé can be said to produce 'good design' uniting the beauty of form, concern for user welfare and the preservation of environment, with speed of construction and appropriateness for the context.

9.6 Final Word: Sustainability, Governance, and Climate-Sensitive Design

Among the characteristics of today's cities, the antagonism between spaces of privilege and exclusion that juxtaposes built landscapes from opposite worlds can be observed. These differences challenge urban planners to develop cities that help citizens to live with quality and access to health, housing and food, through an equitable development. What we commonly see is a lack of urban planning and,

(a) (b) (c) (d)

Figure 9.21. Sarah Network unit — Salvador, BA: (a) external space, (b) inner space, (c) hallway lit naturally (d) swimming pool for patients. (Source: Photographs by Nelson Kon)

in many cases, satisfactory policies and projects. In Latin America in particular, this lacunae leads to an increase in violence, which is further exacerbated by the *process* of urbanization and expansion of slums (Barbosa *et al.*, 2013).

Additionally, the single-minded pursuit of productivity in urban areas has been catastrophic in many cases, particularly in Asia and Latin America. Leaving aside the economic disparity between industrialized and developing countries, such a narrow focus has led to large disparities within countries and especially within cities. Productivity enhancement has led to a form of decision-making favoring the interests of real estate investors and financial entrepreneurs and much less concerned with mitigating and/or solving matters related to governance. Aesthetic factors and monetary valuation of city spaces end up being priority. How can this dynamic be changed?

The implementation and development of democratic governance is not an easy task in the tropical region, since economic interests stand in the way of attempts to establish directions to achieve social equity. A paradigm shift is needed in order to create a new relationship between human activities and nature so that social, environmental and economic equity could be pursued. Fortunately tropical countries seem to have more to gain from actions and strategies that are sensitive to the climate-energy movement. Urban studies play a key role in this scenario, as the cities are the main stage of the antagonism between human activities and the environment. And the problem keeps on growing.

The search for a logical design that acknowledges the constancy of the already existing environment is necessary. It needs to be culturally suitable to a particular place and to use local materials, so that the architectural design itself functions as a mediator between the man and the environment (Romero, 2001).

On the other hand, Emmanuel (2009) points out some difficulties related to the climate-sensitive design in the face of urban climate change. This method seems to be particularly problematic in the urban tropics, which have to deal with an existent "oppressive heat being made worse by the deteriorating urban climate and the lack of financial resources and political will to re-direct urban growth towards more favorable outcome". Some archetypes in tropical design philosophy — such as the efficacy of open buildings with indistinct demarcation between their inner and outer areas — could be put in check when faced with the falling microclimate casts (Emmanuel, 2009).

The climate-sensitive design approach represents more than just a change in style; it is, in fact, a paradigm shift. 'Good design' has to be locally determined by the opportunities offered by the local area and bear in mind the local needs. As this process involves a dynamic relationship over time, it is not possible to produce comprehensive lists discriminating right or wrong procedures.

References

Barbosa, G.S. (2013). O Discurso da Sustentabilidade Expresso no Projeto Urbano, PhD Thesis. PROURB/FAU/UFRJ, Rio de Janeiro, Brazil.

Barbosa, G.S., Drach, P.R.C. and Corbella, O.D. (2010a). A Comparative Study of Sprawling and Compact Areas in Hot and Cold Regions, *Proc. World Renewable Energy Congress 2010*, WREC XI, 1–6 (in English).

Barbosa, G.S., Drach, P.R.C. and Corbella, O.D. (2010b). Um Estudo Comparativo de Regiões Espraiadas e Compactas: Caminho para o Desenvolvimento de Cidades Sustentáveis, *Proc. Congresso Internacional Sustentabilidade e Habitação de Interesse Social*, CHIS, 1–10 (in Portuguese).

Barbosa, G.S., Drach, P.R.C. and Corbella, O.D. (2012). Sustentabilidade urbana e desenvolvimento sustentável: uma discussão em aberto, *Proc. XIV Encontro Nacional de Tecnologia do Ambiente Construído*, ENTAC, 1–6, 10 (in Portuguese).

Barbosa, G.S., Drach, P.R.C. and Corbella, O.D. (2013). Sustainable Development and Urban Sustainability: a review of concepts, *Proc. 8th International Academic Conference*, IISES, 30–45 (in English).

Bruse, M. (2010a) ENVI-met. Version 3.1 BETA III — 2009, On-line Manual. Available at http://www.envi-met.com (latest build 14 December 2009).

Bruse, M. (2010b) LEONARDO 3.75, On-line Manual. Available at http://www.envi-met.com (latest build 14 December 2009).

Corbella, O.D. and S. Yannas. (2003). *Em Busca de Arquitetura sustentável para os Trópicos*, Editora Revan, Rio de Janeiro, Brazil.

Drach, P.R.C. (2012). Ventilation and urban morphology, *NoPa Project Conference: Energy efficiency of public buildings in Brazil.* Team meetings — Universidade Federal do Rio de Janeiro — UFRJ/Universidade Federal do Paraná — UFPR/Technische Universität München — TUM, Palácio Capanema, Rio de Janeiro (in English).

Drach, P.R.C. (2012–2015). Conforto Térmico em Espaços Abertos no Rio de Janeiro: Relação entre Adensamento Urbano e Formação de Ilhas de Calor. Project provided by the Brazilian funding agencies CNPq and CAPES. Number: 401387/2011-9.

Drach, P.R.C., Barbosa, G.S. and Corbella, O.D. (2014). Densification Process of Copacabana Neighbourhood over 1930, 1950 and 2010 Decades: comfort indexes, *Proc. 3rd International Conference on Countermeasures to Urban Heat*, IC2UHI, 1–12.

Emmanuel, R. (2005). *An urban approach to climate-sensitive design: strategies for the tropics*, Taylor and Francis, London, UK.

Emmanuel, R. and Fernando, H.J.S. (2007) Urban heat islands in humid and arid climates: role of urban form and thermal properties in Colombo, Sri Lanka and Phoenix, USA. *Clim. Res.*, **34**(3), 241–251.

Emmanuel, R. (2009). Sustainable urbanity and urban climate change: amelioration of uhi's as a quality-of-life agenda for tropical mega-cities, *The seventh International Conference on Urban Climate*, Yokohama, Japan.

Fathy, H. (1986). *Natural Energy and Vernacular Architecture: Principles and Examples with Reference to Hot Arid Climates*, University of Chicago Press, Chicago, IL.

Girardet, H. (2007). *Creating Sustainable Cities*, Green Books LTD/The Schumacher Society, Bristol, UK.

Ghione, R. (2014). Transformação social e urbanística de Medellín. *Minha Cidade*, São Paulo, ano 14, n. 166.07, Vitruvius. Available at http://www.vitruvius.com.br/revistas/read/minhacidade/14.166/5177.

ISO 10551 (1995) Ergonomics of the thermal environment — Assessment of the influence of the thermal environment using subjective judgement scales, Geneva, Switzerland.

Leal, L.P. (2010). Desafios para a requalificação da região portuária do Rio de Janeiro: Desfazendo os estigmas sociais e a segregação, *I Enamparq*, Rio de Janeiro, Brazil.

Lima, J.F. (2004). *O que é ser arquiteto: memórias profissionais de Lelé (João Filgueiras Lima); em depoimento a Cynara Menezes*, Record, Rio de Janeiro, Brazil.

Lima, J.F. (2009). *CTRS, Centro de Tecnologia da Rede SARAH*, Sarah/Letras, University of Texas, Austin, TX.

Lima, J.F. (2012). *Arquitetura — uma Experiência na Área da Saúde João Filgueiras Lima — Lelé*, Col. Coleção Capa Dura — Romano Guerra.

Lombardo, M.A. (1985). Ilha de Calor nas Metrópoles: O Exemplo de São Paulo, São Editora HUCITEC, São Paulo, Brazil.

Moore, W. (1998). *Ecodemocracia:El modelo Pós-Capitalista*, EMED and CEIS Eds, Buenos Aires, Argentina.

Oliveira, S., Andrade, H. and Vaz, T. (2011). The cooling effect of green spaces as a contribution to the mitigation of urban heat: a case study in Lisbon, *Build Environ.*, **46**(11), 2186–2194.

Rabha, N.M. de C.E. (2004). Bairros Portuários: Aspectos Sociais e Culturais, in: Schweiser, Peter; Cesario, Sebastiana, *Revitalização de Centros Urbanos em Áreas Portuárias*, Viveiros de Castro, Rio de Janeiro, Brazil.

Rogers, R. (1998). *Cidades para um pequeno planeta (Cities For A Small Planet)*, Editora Gustavo Gili, Barcelona, Spain.

Rogers, R. and Gumuchdjian, P. (2000). *Ciudades para un pequeño planeta (Cities For A Small Planet)*, Editora Gustavo Gili, Barcelona, Spain.

Romero, M.A.B. (2001). *Arquitetura Bioclimática do Espaço Público*, Editora Universidade de Brasília, Brasília, Brazil.

Sequera, J. and Mateos, E. (2014). Micro-resistencias de la vida cotidiana. las fracturas de las políticas urbanas neoliberales en Puerto Madero, Buenos Aires (Micro-resistances of everyday life. The Fractures of neoliberal urban policies in Puerto Madero, Buenos Aires), *Scripta Nova — Revista Electrónica de Geografía y Ciencias Sociales*, XVIII, **493**(22), 1–17.

Tella, G. (2010). Puerto Madero, cuando el concurso es la herramienta, *Revista de Arquitectura de la Sociedad Central de Arquitectos*, **237**, 60–67.

Vescina, L.M. (2010). *Projeto urbano, paisagem e representação: alternativas para o espaço metropolitano*, PhD Thesis (Doutorado) — UFRJ/PROURB/Programa de Pós-Graduação em Urbanismo, Brazil.

Chapter 10

Integration of climate knowledge in urban design and planning

Gerald Mills

Anthropogenic emission of greenhouse gases (GHG) causes global climate change (GCC); addressing this issue requires policies for adaptation (to cope with the changing climate) and mitigation (to limit the magnitude of change). Applying these policies at the urban scale is critical for three main reasons. First, cities are located in landscapes that are exposed many of the natural hazards (e.g. sea-level rise) that are likely to be exacerbated by GCC. Second, cities are responsible for the majority of CO_2 emissions owing to the focused use of fossil fuels by industry, transport and buildings. Third, most cities have existing planning systems that can be used to apply GCC policies. However, cities are also of intensive local climate changes (such as the urban heat island) that have been measured and studied for decades. Some of the processes responsible for the urban climate (UC) are also linked to the drivers of GCC so that addressing climate change at one scale has an impact on the other. Naturally, it is important that climate change policies at either scale are complementary; otherwise, GCC strategies may give rise to countervailing outcomes at the urban scale and vice versa. This requires that policy must account for the hierarchy of climate scales and of anthropogenic drivers. Given the importance of cities, an understanding of urban climates is needed to integrate GCC actions into planning and design. In this chapter, strategies for mitigation and adaptation to climate change are placed within the context of urban actions to create climatically convivial places in warm, tropical climates.

10.1 Introduction

The 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2013) has concluded that "warming of the climate system is unequivocal and that it is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century." The evidence for this comes from an array of observations made at the Earth's surface and from satellite platforms coupled with our understanding of Earth–atmosphere processes. The latter are encapsulated by Earth system models that have become increasingly sophisticated and precise in their projections; however, the spatial resolution of most models remains too large to resolve processes and outcomes at regional scales. The primary anthropogenic drivers of GCC are emissions of GHG and landscape change, which have modified the energy budget of the Earth-Atmosphere System (EAS). Urbanization has a key role to play directly and indirectly as a locus for these drivers. Cities are increasingly recognized as a scale where there is an institutional capacity to regulate the drivers of GCC and manage its consequences. As a result many of the GCC responses have been 'mapped' to the urban scale even though the projections of models provide limited guidance on outcomes for individual cities.

Independently of GCC, cities have profound impacts on the local atmosphere and hydrology. The urban atmosphere is generally warmer, more turbulent and more polluted and the urban hydrology is more responsive to precipitation events. These changes are the result of the replacement of much of the pre-urban landscape by a surface that is hard, impermeable, built-upon and drained. It is also a result of emission of waste heat, gases and materials into the air, soil and water. These changes have been the subject of study for more than 200 years and until the mid-20th century, the urban climate effect was considered to be the only clear evidence of the impact of humans on climate. The most recognizable of these effects is the urban heat island, which describes warmer air and surface temperature in cities when compared to the surrounding 'natural' landscape.

In most wealthy cities a concern for the health consequences of poor air and water quality has given rise to planning policies to address these issues; however. more broad-based initiatives to manage the urban climate have generally not been applied, even though there is a significant body of work on the causes of urban climate effects and their impacts on public health and urban energy use. Concern for GCC has provided an impetus for developing urban-based climate policies but to be effective, these must address climate change and its causes across a spectrum of scales, from the building to the city to the regional and global.

In this chapter I discuss how climate knowledge may be integrated into urban planning and design and how best to achieve climate objectives at these different scales. Initially, I introduce climate changes at global and urban scales and our current assessment of the implications for cities in tropical climates.

10.2 Global Climate Change Science

The physical science that underpins GCC is linked to the increased concentration of GHG in the atmosphere, which has modified its radiative absorption spectrum and enhanced the Earth's natural greenhouse effect. To assess the climate over the next 100 years, the IPCC considered four scenarios, termed representative carbon pathways (RCPs) to represent different emission trajectories; each is identified by their approximate total radiative forcing in year 2100 relative to 1750: 2.6 $W \cdot m^{-2}$ for RCP2.6, 4.5 $W \cdot m^{-2}$ for RCP4.5, 6.0 $W \cdot m^{-2}$ for RCP6.0, and 8.5 $W \cdot m^{-2}$ for RCP8.5. The IPCC concluded that global surface temperature change is likely to exceed 1.5°C relative to 1850 to 1900 for all scenarios except RCP2.6; moreover, temperature under RCP6.0 and RCP8.5 will likely exceed 2°C. Although global warming has become synonymous with anthropogenic GCC, the projected changes to the EAS are systemic and affect all its components, including the circulation systems that

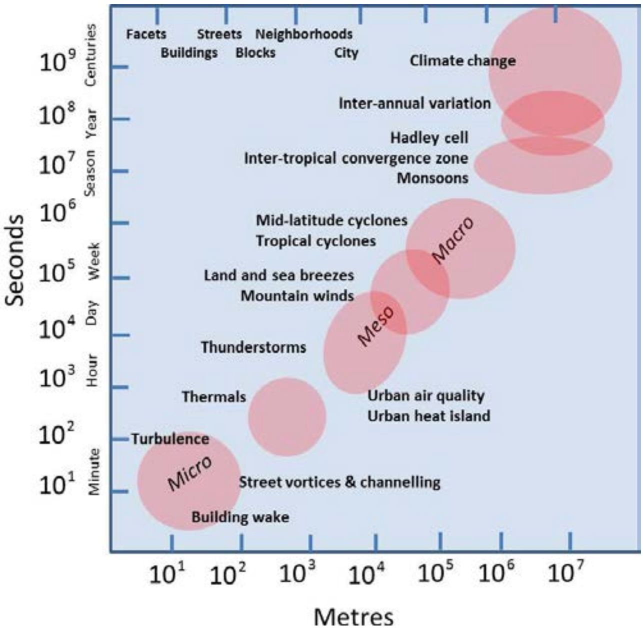


Figure 10.1. Time and space scales of atmospheric motion abstracted from The COMET Program.[1] The dimensions of urban features are shown in the upper left corner and the scales of urban effects are shown on the lower half. Urban climate effects are embedded with a larger climate context.

govern weather. For the tropics, the current projections suggest that the Hadley circulation is likely to slow down but will widen, extending sub-tropical dry climates into the mid-latitudes. Elsewhere in the wet tropics where much of the precipitation occurs as intense short-duration events, more intense and frequent events are very likely.

Table 10.1 lists some of the observed and projected climate changes and the human contribution. These include general warming (especially at night) and more frequent hot spells, more intense rainfall events, more frequent and persistent droughts, increased tropical

[1]COMET® Website at http://meted.ucar.edu/ of the University Corporation for Atmospheric Research (UCAR), sponsored in part through cooperative agreement(s) with the National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Commerce (DOC). © 1997–2015 University Corporation for Atmospheric Research. All Rights Reserved.

Table 10.1. Examples of possible impacts of GCC due to changes in extreme weather and climate events, based on projections to the mid to late 21st century. These do not take into account any changes or developments in adaptive capacity. The likelihood estimates in column two relate to the phenomena listed in the column of the left. (Source: compiled from IPCC (2007, 2013))

Phenomenon[(a)] and direction of trend	Evidence of change/human contribution	Likelihood of further change by late 21st century	Impact on cities
Warmer and/or fewer cold days and nights over most land areas. Warmer and/or more frequent hot days and nights over most land areas.	Very likely Very likely	Virtually certain	Reduced energy demand for heating; increased demand for cooling; declining air quality; reduced disruption to transport due to snow, ice; effects on winter tourism.
Warm spells/heat waves. Frequency and/or duration increases over most land areas.	Medium confidence Likely	Very likely	Reduction in quality of life for people in warm areas without appropriate housing; impacts on the elderly, very young and poor.
Heavy precipitation events. Increase in the frequency, intensity and/or amount of heavy precipitation.	Likely Medium confidence	Very likely over most of the mid-latitude land masses and over wet tropical regions.	Disruption of settlements, commerce, transport and societies due to flooding; pressures on urban infrastructure; loss of property.
Increases in intensity and/or duration of drought.	Low confidence Low confidence	Likely on a regional to global scale.	Water shortage for settlements, industry and societies; reduced hydropower generation potentials; potential for population migration.

(*Continued*)

Table 10.1. (*Continued*)

Phenomenon[(a)] and direction of trend	Evidence of change/human contribution	Likelihood of further change by late 21st century	Impact on cities
Intense tropical cyclone activity increases.	Low confidence Low confidence	More likely than not in the western North Pacific and North Atlantic.	Disruption of urban infrastructure by flood and high winds; withdrawal of risk coverage in vulnerable areas by private insurers; potential for population migrations; loss of property.
Increased incidence and/or magnitude of extreme high sea level.	Likely Likely	Very likely	Costs of coastal protection versus costs of land-use relocation; potential for movement of settlements and infrastructure; also see tropical cyclones above.

cyclone activity and higher sea-levels. Note that the observational evidence (and the human contribution) for each of these varies in its certainty; there is greater certitude about the continuation of these trends into the 21st century, especially in the case of global warming. The potential impacts of GCC on society are dramatic and include food security, water resources, health, coastal flooding and so on; not surprisingly, preventive and preparatory actions (so called 'no regrets' policies) are needed.

10.2.1 *Policy responses*

Responses to GCC fall into the two overlapping categories of mitigation and adaptation. Mitigation actions are designed to offset or stop the human-caused drivers of climate change, namely emissions of GHG and landscape change. While there are many sources of GHG, fossil fuel consumption is the largest contributor so energy-use policies are a central theme of a mitigation strategy. Typically these policies include: increased efficiency of fossil fuel use; development of renewable energy sources and; modifying societal/personal behavior patterns. The corollary to limiting GHG emissions is to enhance the ability of the landscape to extract and store atmospheric carbon; typically this is done through afforestation programs, although geoengineering projects attempt to do the same. Ideally, these efforts will foster a 'zero-carbon' society in which any human emissions are offset by counteracting actions (Lehmann, 2014).

While global mitigation is needed to moderate GCC, some change will certainly occur owing to historic emissions. Moreover, even if some countries enact mitigation measures, others may not. Adaptation describes those policies designed to cope with GCC scenarios and are often framed in the language of risk management, which incorporates three distinct attributes: hazard, exposure and vulnerability. The statistics of climate and weather define a hazard but the other two attributes are outcomes of human decisions and societal make-up. Exposure refers to the infrastructure and population that will be affected by the hazard while vulnerability measures the ability of the population or economy to cope with the hazards. Risk lies at the intersection of these attributes. It is exposure and vulnerability together that represent the human component of risk; a goal of much of GCC adaptation policy is to achieve resilience by creating societal, economic and urban infrastructures that can withstand climate shocks.

Until very recently, these responses to GCC had been co-ordinated through global politics and international agreements among sovereign states. At the core of these agreements is a commitment to mitigate by limiting the emission of GHG and there are established protocols for collating national inventories. However, progress on addressing GCC has been fitful even as the evidence for the anthropogenic contribution has strengthened. The main reason is of course the reliance on fossil fuel energy use for conventional economic development and prosperity. This has created disputes regarding the costs of compliance, loss of competitive advantages, historic responsibility for the elevated GHG concentrations and on financing mitigation and adaptation actions.

10.2.2 *Cities and global climate change*

Over the last ten years the role of cities (and their management systems) in GCC has grown in prominence; the latest 5th IPCC report is the first to explicitly discuss urban areas in terms of both mitigation (Seto *et al.*, 2014) and adaptation (Revi *et al.*, 2014). In addition, several international networks of towns and cities have emerged to consider how best to address GCC at urban scales (see Acuto (2013) on the C40 Cities Climate Leadership Group). The urban scale represents a geographical nexus that links society, economy and environment to global-scale climate change for a number of reasons.

First, cities are a significant source of GHG emissions; it is estimated that they are responsible for between 71% and 76% of CO_2 emissions from global final energy use (IPCC, 2013). However, there is ongoing debate about how best to account for the urban contribution to global GHG emissions. This is partly because of the geographical mismatch between where energy is used (to generate electricity, for example) and where the ‘product’ is consumed. Where comparable data does exist for cities (e.g. Kennedy *et al.*, 2009) the complex nature of local economies is revealed, such as the reliance on a particular economic sector (such as services) or the availability of hydroelectric power. This indicates the importance of completing an inventory of GHG emissions at the urban scale to guide urban mitigation actions.

Second, cities are at particular risk from current and projected GCC phenomenon (Table 10.1). This is partly a result of site selection; most cities developed at low elevations, close to coasts and along rivers (Small, 2004). These topographic settings may experience the hazards of flooding by rivers and sea-level rise and strong winds from offshore storms. However, the effects of these hazards is also contingent on the nature of urban development, such as whether floodplains are built upon, or the strength of building materials. GCC will alter exposure to these hazards by modifying the statistics of hazardous events, such as the frequency of intense rainstorms. However, the risk experienced by urban neighborhoods will vary according to their current and future vulnerability.

Third, cities have planning systems and, to varying degrees have greater authority to manage land use/land cover, building form and layout, transportation, etc. than non-urban areas. This means that they occupy a unique position in their ability to respond to GCC. According to the C40 group, "our cities are informing and shifting the global conversation on climate change because they have shown themselves to be uniquely capable of devising and implementing climate change solutions — both reducing emissions and increasing urban resilience" (ARUP, 2014). In addition, they occupy relatively small areas where the main sectoral drivers of GCC (transport, buildings and industry) are proximate. As a result there is considerable opportunity for addressing many issues together (so-called co-benefits), such as urban air quality and GCC, both of which are strongly linked to fossil fuel consumption.

Not surprisingly then, many of the global- and national-scale approaches to dealing with climate change have been mapped to urban scales. For example, protocols of the estimation of GHG emissions have been established following the same rationale as that used for national inventories (WRI/C40/ICLEI, 2014). Such data is essential to guide mitigation strategies in individual cities, even though many of the major drivers of GHG emissions are outside the control of most cities (See Table 1.3). Managing urban form through land-use control coupled with infrastructure planning is considered the most effective means of using urban planning tools for maximum effect. There is a considerable body of evidence that suggests that compact and densely occupied cities that are served by public transit are inherently more energy efficient than dispersed, low-density cities (e.g. Kenworthy, 2006). However, it is acknowledged that density can be measured in several different ways and built density (e.g. built area fraction or floor area ratio) may not correspond with population density (Boyko and Cooper, 2011).

Currently, GCC projections provide information on the background climates of cities; to transfer these to the scale of a city, results must be downscaled using either statistical or dynamic models. Typically, in such assessments cities have been treated as fixed entities so that while the climate changes, the city remains static — the co-evolution of climate and cities is a relatively new area of research (Masson *et al.*, 2014). As the outcomes of climate change will vary geographically, adaptive measures are often based on evaluation of risk that is experienced under current climate conditions on the assumption that these risks are likely to increase under climate change. The World Bank (2011) suggests that an initial assessment of vulnerability, risk and adaptive capacity in city operations, specific sectors and different communities and demographic groups be done to frame any adaptive policy. There is a strong emphasis in much of the literature on city networks as a means of sharing mitigation.

10.3 Urban Climate Change Science

In addition to contributing to GCC, cities modify the background climate in their vicinity profoundly due to their form and function (Fig. 10.2). Urban form includes the surface cover, the fabric and the structure of the city. The cover describes the plan area of the city and the proportion that is covered by paving, by buildings and by vegetation. The fabric refers to the construction materials, which are usually dense and impermeable. The structure of a city describes its 3D geometry; i.e. the dimensions of the buildings and the intervening spaces. Urban function incorporates the range of human activities that sustains the occupation of the city and requires the throughput of energy and materials. Some of this input increases the stock of the city (i.e. adds to or modifies the form) but much of it is expended as waste heat and materials that are deposited into the air, the water and the soil.

At the urban scale, the surface that the overlying atmosphere encounters is rough, usually dry and warm. It is also a source of particulates and gases. Chapter 8 showed in detail the energetic processes in the overlying air forming an urban boundary layer (UBL) as

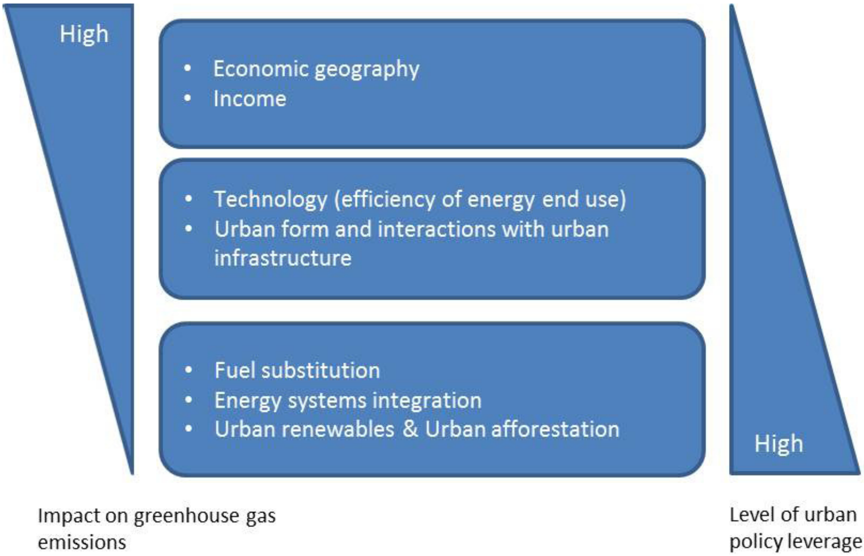


Figure 10.2. Stylized hierarchy of drivers of urban GHG emissions and policy leverages by urban-scale decision making (redrawn from Seto *et al.*, 2014). Cities have relatively little control over some of the major drivers of GHG emissions but have large control over the minor drivers; the middle level where cities can manage urban form and infrastructure together and regulate energy use in transport and buildings represents the urban tool that has greatest influence.

well as the urban canopy layer (UCL) — the lowest part of the UBL that extends from the ground to the mean height of buildings. The urban effect on climate within the UCL — the urban heat island (UHI) — is of particular relevance for GCC, as it may accentuate the warming projections and place additional heat burden on many urban dwellers during heatwave events, especially those that are vulnerable to heat stress.

10.3.1 *Policy responses*

Until very recently, climate knowledge had not been employed into routine urban planning and design decision-making in most places (Hebbert and McKillop, 2013). There are many reasons that can be advanced for this, including: the subtle nature of many urban climate changes; the difficulty in translating complex ideas into policy;

advances in technology that can trump design solutions; and an emphasis on planning for social and economic outcomes to the exclusion of environmental concerns. As a result, for most cities (including those in high-income countries) there are no coherent guidelines to integrate climate knowledge generally — the exception is usually air quality management. Instead, climate policies are adopted on a city-by-city basis in response to events, such as heatwaves and the role of the UHI.

In the case of the UHI there is a substantial body of evidence on its mitigation through the selection of construction materials (e.g. to increase permeability to rainwater), surface cover (e.g. to increase reflection and reduce heat gain) and increasing vegetative cover (e.g. to provide shade and increase evaporation). These interventions are applied to different facets to address heat gain on the building envelope or on outdoor surfaces (see http://www.epa.gov/heatisland/ for examples). The UHI could also be addressed through modification of urban geometry to limit long-wave-radiation trapping within the urban canopy layer and increase ventilation (Ng, 2009); however, this is difficult to do once the city is built. Reducing the UHI effect should also decrease the cooling demand in many cities and contribute indirectly to mitigating GHG emissions. It is important to note that a naïve approach to urban design could increase urban density so as to reduce energy requirements in line with concerns for GHG emissions while simultaneously reducing near-surface air ventilation, worsening air quality and enhancing the air UHI and increasing thermal heat stress (Martilli, 2014). Getting the right balance between building density and vegetative cover is a design challenge that must consider the geographical setting of the city, including its background climate.

The most sophisticated and comprehensive exemplar for integrating climate into urban planning and design is the Office for Environmental Protection of the City of Stuttgart (Germany), which was formed in 1938 (www.stadtklima-stuttgart.de) to cope with poor air quality (Hebbert and Jankovic, 2013). It has since evolved a planning methodology that is based on an assessment of the local climate resource available to a settlement. The resulting climate map analyzes the character of the local landscape (including that which has been urbanized) in terms of its (un)desirable climatic properties. The planning process utilizes these maps in making decisions about the nature and type of urban development so as to protect natural systems. In particular there is a strong focus on the character of the natural topography and its potential as a source of cool and clean air for the settlement. In the Stuttgart region the emphasis is on katabatic flows from the surrounding hillsides that are channeled into the city; however, elsewhere the concern may be on sea-breeze flows (Ren *et al.*, 2011). The great advantage of the approach is its use of planning methods and tools to assemble climate information and inform a dialogue between scientists and urban planning practitioners.

10.4 Tropical Climates, Climate Change and Cities

Although the majority (54%) of the world's population now lives in urban areas, there is considerable regional variation. The populations of Asia and Africa are the least urbanized currently (40% and 48%, respectively) but this is where future urban population growth will be concentrated; India, China and Nigeria are expected to account for 37% of this growth between 2014 and 2050 (UN, 2014). While most cities are relatively small (<500,000 inhabitants), the global urbanization process is captured in Table 10.2, which classifies the largest cities of the world (≥750,000 in 2010) according to Köppen–Geiger climate type and the income level of the country. There are several notable points here. First, the number and aggregate population of large cities in tropical climates is growing rapidly; in 1950 cities in 'A' climates accounted for just 13% of the large city population, but in 2010 they accounted for 23%. Moreover, there are now over 50 cities that occupy arid and warm (BSh and BWh) climates, where water resources are limited. Second, most of these tropical cities are located in countries with low per capita income levels; while cities like Hong Kong and Miami are relatively wealthy, Dhaka and Kampala are more representative of this category. By comparison, the cities located in mid-latitude (C and D) climates are relatively wealthy.

Table 10.2. A breakdown of the world's major cities (>750,000) based on Köppen–Geiger climate type (Kottek *et al.*, 2006). The population data (in thousands) is from Hugo Ahlenius, Nordpil (http://nordpil.com) and is based on UN Population Division and World Urbanization Prospects, 2007 Revision. The income categories are those of the World Bank (www.worldbank.org): low-income economies are defined as those with a GNI per capita, of $1,045 or less in 2013; middle-income economies are those with a GNI per capita of more than $1,045 but less than $12,746; high-income economies are those with a GNI per capita of $12,746 or more. Lower-middle-income and upper-middle-income economies are separated at a GNI per capita of $4,125.

				Number of cities Per capita income ($)				
Köppen climate type	Pop 1950	Pop 2010	Pop 2050	High	Upper middle	Lower middle	Low	Total number of cities
Equatorial (A) $T_{\min} \geq +18°C$	52010	319360	464791	4	38	65	20	127
Arid (B)[1]	24650	169430	247964	12	37	29	4	82
BSh	7240	9250	11640	2	10	17	4	33
BWh	9810	12510	16300	7	5	8	0	20
Warm temperate (C) $-3°C < T_{\min} < +18°C$	241330	725700	890317	101	144	40	5	290
Snow (D) $T_{\min} \leq -3°C$	72350	182140	217004	43	35	8	4	90
Polar (E)[2] $T_{\max} < +10°C$	370	1590	2178	0	0	1	0	1
Total	390710	1398220	1822254	160	254	143	33	590

[1]Arid climates are defined principally on the basis of precipitation; steppe (BS) and desert (BW) climates with $T_{min} \geq +18°C$ are warm (h).
[2]The only city in this category is La Paz (16.5°N) which has an altitude of 3500 m ASL.

Finally, tropical climates are warm so there is a significant cooling energy need for much of the year (see Chapter 1).

These statistics have obvious implications for GCC. As a general rule, per capita GHG emissions increase with income levels (Fig. 10.2) so most tropical cities have low per capita contribution to GCC. Consequently, climate change actions need to ensure that GHG emissions do not rise, even as cities become more prosperous. While the relationship between urban form and transport emissions is largely invariant with climate, the same is not true of building energy demand. In tropical climates, the chief energy need is for cooling and if this is met by mechanical air-conditioning systems (as it is currently in more prosperous cities), energy use will increase quickly. For example, in Shanghai air conditioning already accounts for over 30% of the cities' total energy consumption (Li and Tao, 2009).

The design challenge is to offset the undesirable aspects of the urban climate while limiting GHG emissions. In the case of hot and humid climates this means minimizing/maximizing heat loss from buildings, ensuring ventilation of the UCL and minimizing the surface and air UHI. At a building scale, a rectangular plan area is best — ideally the long axis is oriented so as to minimize solar gain via the roof and maximize airflow through the envelope (Fig. 10.3). In many respects tall buildings are suited to these climates as the

Figure 10.3. The Singapore School of the Arts building incorporates many of the traditional architectural responses to a hot and humid climate. The rectangular shape creates an envelope that is large compared to its volume (enhancing heat loss and exposing a small roof area to direct solar gain). The building is raised to access faster moving air, and the envelope is permeable to allow air to ventilate the building. (Source: School of the Arts, Singapore by Katmorro is licensed under creative commons)

high solar altitude minimizes heat gain through the walls and the upper floors have access to faster flowing air. However, there are limits to this strategy at an urban scale unless design provides ventilation pathways (as detailed in Chapter 4) or intersperses taller and lower buildings to maximize roughness. In hot and arid (B) climates the primary concern is for daytime heat stress, as nights are often cool. Here a strategy that limits the daytime surface UHI but promotes the nighttime air UHI is ideal from a thermal perspective. In these climates, there is a great deal be gained from clustering the built stock so that buildings provide mutual shade during the daytime and nighttime heat loss is reduced (Johansson, 2006).

10.5 Integrating Climate Knowledge into Urban Planning Practice

Concerns about GCC have provided an impetus for including climate issues into the routine practices of urban planning and design. However, implementing actions in low-income cities is hampered both by a lack of resources and, in many cases, weak planning structures (and powers). For example, in Lagos unregulated growth has allowed densely occupied and poorly constructed settlements to extend into lagoons throughout the city and up to 6 million could be displaced if the sea-level were to rise by 2 m (LSG, 2012). Consequently, much of the literature on GCC and poorer cities has concentrated on city governance rather than on specific responses to climate changes. Where guidelines are provided, they are often general in nature and do not account for the local-scale climate changes that will (or have) result from urbanization. This is partly because the knowledge on climate changes across a spectrum of scales has not been integrated; hence guidelines for climate management at one scale may be contradicted at another.

When considering how to incorporate GCC policies at urban scales it is worth making some general points:

Distinguish between new and existing settlements. The best opportunity for incorporating climate is prior to construction; once the settlement is in place change becomes more difficult and is constrained by prior decisions. Probably the most important decision is that of site location (at city and neighborhood scale) as this will determine the degree of exposure to hazards. Thereafter, urban land-use, street design and built density set the context for population density and transportation patterns. Urban design is critical at this point as radically different built configurations (and climatic effects) can be achieved that follow planning guidelines on density, greenspace, etc. The 'best' urban design is context-dependent and should be adapted to the local background climate.

The importance of scale. Urban policies should be cognizant of the impacts of decisions at one scale on outcomes of another. For example, a tenet of GCC policies is that more compact and densely occupied cities are more energy efficient. However, if this policy is realized through tall, closely spaced buildings and little vegetative cover, the air UHI will be enhanced and ambient wind speed at street level reduced. In a warm and humid climate, this will increase the cooling energy of buildings (See Chapter 9 for an example).

Linking policy action to desirable outcome. A given action can have many effects but it is important to make the likely effects explicit. For example, one action to reduce the UHI is to introduce cool roofs, usually through the use of light-colored tiles or paint. However, while this will certainly impact the surface UHI (and reduce building cooling energy demand) it may have little impact on air UHI at street level.

Meet goals simultaneously. One of the great advantages afforded through urban planning is the opportunity to avail of co-benefits; for example reducing energy demand should both mitigate GHG emissions and improve air quality. At the same time, it is unlikely that one tool can accomplish all goals. For example, city greening policies can help regulate several undesirable aspects of urbanization such as providing hydrological services, reducing air temperature and scavenging airborne pollutants (Nowak, 2006). However, a tree-planting program at a city scale that is designed to mitigate CO_2 emissions will have a small impact owing to the limited capacity of tree sequestration and the magnitude of GHG emissions in cities (Fig. 10.2).

A good starting point in any evaluation of the climate impact of a city is to create a detailed geographical database on both land cover and land use. The former describes the physical character of the city (surface cover, materials, built geometry) and its 'natural' geographic setting (e.g. rivers, coasts and mountains). Information on vegetative and impervious surface covers and built density is especially useful for evaluating the urban climate and informing mitigation actions. Land use describes the occupation of space and should describe the spatial distribution of urban functions (e.g. residential, commercial, etc.) and of population. These databases should adopt a common framework to describe the urban landscape (such as the local climate zone, Stewart and Oke, 2012 and Chapter 7) at different planning scales (region, city, neighborhood, building) to structure information and to allow comparison with other places. These data are needed to assess the opportunities for mitigation and to support a risk analysis by overlaying the distributions of natural hazard, exposure and vulnerability. Ideally, an observation program would maintain information on urban (re)development and its consequences though measurements of key variables such as energy use, air quality and weather to evaluate the efficacy of mitigation and adaptation actions.

Much of this information is not available even in cities with considerable resources; elsewhere, the data may have been gathered at different scales and in an *ad hoc* and fragmented manner so that compilation into a useful resource is difficult. However, freely available satellite and terrain data (e.g. Landsat) coupled with simple on-the-ground neighborhood surveys can provide a starting point for gathering relevant urban data. Chapter 7 provides an example for a tropical city. In the absence of such databases to provide a framework it is not possible to integrate climate knowledge to planning practice at a place.

10.6 Conclusions

With few exceptions, climate information has not been integrated into urban planning and design practice. However, the recognition of the role of cities as drivers of GCC and a concern for the impacts of

GCC at urban scales provide an opportunity to do so. However, it will be important to ensure that urban-scale policies are compatible with local and global outcomes; this requires geographically specific actions that are tuned to the local background climate. An effective climate-based urban policy requires both a planning structure to implement mitigation and adaptation actions, and a spatial framework to inform policy and guide these actions at different urban scales.

References

Acuto, M. (2013). The new climate leaders, *Review of International Studies*, **39**(04), 835–857.

ARUP (2014). *Climate Action in Megacities: C40 Cities Baseline and Opportunities, Volume 2*. Available at http://c40.org/blog_posts/CAM2.

Boyko, C.T. and Cooper, R. (2011). Clarifying and re-conceptualising density, *Progress in Planning*, **76**, 1–61.

Hebbert, M. and Jankovic, V. (2013). Cities and climate change: the precedents and why they matter, *Urban Studies*, **50**, 1332–1347.

Hebbert, M. and Mackillop, F. (2013). Urban climatology applied to urban planning: a postwar knowledge circulation failure, *International Journal of Urban and Regional Research*, **37**, 1542–1558.

IPCC (2007). Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

IPCC (2013). Stocker, T.F., Qin, D., Plattner, G.K. *et al.* (eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK.

Johansson, E. (2006). Influence of urban geometry on outdoor thermal comfort in a hot dry climate: a study in Fez, Morocco, *Building and Environment*, **41**(10), 1326–1338.

Kennedy, C., Steinberger, J., Gasson, B. *et al.* (2009). Greenhouse gas emissions from global cities, *Environmental Science and Technology*, **43**(19), 7297–7302.

Kenworthy, J.R. (2006). The eco-city: ten key transport and planning dimensions for sustainable city development, *Environment and Urbanization*, **18**, 67–85.

Kottek, M., Grieser, J., Beck, C. *et al.* (2006). World Map of the Köppen–Geiger climate classification updated, *Meteorologische Zeitschrift*, **15**, 259–263.

Lehmann S. (ed.) (2014). *Low Carbon Cities: Transforming Urban Systems*, Earthscan, Oxford, UK.

Li, B. and Yao, R. (2009). Urbanisation and its impact on building energy consumption and efficiency in China, *Renewable Energy*, **34**, 1994–1998.

LSG (2012). *Climate Change Policy, 2012–2014*, Lagos State Government, Ministry of the Environment March 2012. Available at http://developmentdiaries.com/wp-content/uploads/2013/03/Lagos-State-Climate-Change-Policy-First-Draft_27.03.2012.pdf.

Masson, V., Marchadier, C., Adolphe, L., Aguejdad, R., Avner, P., Bonhomme, M., Bretagne, G., Briottet, X., Bueno, B., de Munck, C., Doukari, O., Hallegatte, S., Hidalgo, J., Houet, T., Le Bras, J., Lemonsu, A., Long, N., Moine, M.-P., Morel, T., Nolorgues, L., Pigeon, G., Salagnac, J.-L., Viguié, V., Zibouche, K. (2014). Adapting cities to climate change: A systemic modelling approach, *Urban Climate*, **10**, 407–429.

Martilli, A. (2014). An idealized study of city structure, urban climate, energy consumption, and air quality, *Urban Climate*, **10**, 430–446.

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**, 1478–1488.

Nowak, D.J. (2006). Institutionalizing urban forestry as a "biotechnology" to improve environmental quality, *Urban Forestry and Urban Greening*, **5**, 93–100.

Ren, C., Ng, E.Y.Y. and Katzschner, L. (2011). Urban climatic map studies: a review, *International Journal of Climatology*, **31**, 2213–2233.

Revi, A., Satterthwaite, D.E., Aragón-Durand, F. *et al.* (2014). "Urban areas", in Field, C.B., Barros, V.R., Dokken, D.J. *et al.* (eds.) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK, 535–612.

Seto, K.C., Dhakal, S., Bigio, A. *et al.* (2014). "Human Settlements, Infrastructure and Spatial Planning", in Edenhofer, O., Pichs-Madrugs, R., Sokona, Y. *et al.* (eds.) *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK.

Small, C. (2004). Global population distribution and urban land use in geophysical parameter space, *Earth Interactions*, **8**, 1–18.

Stewart, I.D. and Oke, T.R. (2012). Local climate zones for urban temperature studies, *Bulletin of the American Meteorological Society*, **93**(12), 1879–1900.

The World Bank (2011). *Guide to Climate Change Adaptation in Cities*. Available at http://siteresources.worldbank.org/INTURBANDEVELOPMENT/Resources/336387-1318995974398/GuideClimChangeAdaptCities.pdf.

UN (2014). *World Urbanization Prospects: The 2014 Revision, Highlights (ST/ESA/SER.A/352)*, United Nations, Department of Economic and Social Affairs, Population Division, New York, NY.

WRI/C40/ICLEI (2014). *Global Protocol for Community-Scale Greenhouse Gas Emission Inventories*. Available at www.ghgprotocol.org.

This page intentionally left blank

Index

T

U