Urban Design and Outdoor Thermal Comfort in Warm Climates

Studies in Fez and Colombo

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The financial support provided by the Swedish International Development Cooperation Agency (Sida) is gratefully acknowledged.

Abbreviations

ADER-Fès	Agence de Dédensification et de Réhabilitation de la médina de Fès
ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
AUSF	Agence Urbaine et de Sauvegarde de Fès
CMC	Colombo Municipal Council
CMR	Colombo Metropolitan Region
ET*	New effective temperature
FAR	Floor area ratio
H	Height of buildings
LST	Local standard time
MRT	Mean radiant temperature
PET	Physiologically equivalent temperature
PMV	Predicted mean vote
RH	Relative humidity
SET*	New standard effective temperature
SVF	Sky view factor
UCL	Urban canopy layer
UDA	Urban Development Authority (Sri Lanka)
UHI	Urban heat island
UME	Urban moisture excess
VP	Vapour pressure
W	Distance between buildings in a street canyon

1 Introduction

1.1 Background

In 2000, the proportion of the world's population living in the tropical climate zone was estimated at about 40% (Landsberg 1984, OTS 2006). Most tropical countries are developing countries and most are experiencing rapid urbanization. During the period from 1990 to 2020, the urban population in the developing world is expected to increase by about 25–45%, except in Latin America and the Caribbean where the urban population already exceeds 70%. By 2020, the urban population is expected to be greater than the rural population in all parts of the world except sub-Saharan Africa and South Asia (World Bank 2002). Rapid urbanization in developing countries is often regarded as negative, causing poor housing conditions, poverty, environmental problems, ill-health, etc. However, despite the problems brought by urbanization, urban areas are important in a national perspective, since they experience a high level of economic growth (Tannerfeldt and Ljung 2006).

Urban areas act as climate modifiers. Climate elements, such as solar radiation, air temperature, humidity and wind are affected by the urban fabric. Nocturnal urban-rural temperature differences of 6°C or more are common in the centres of major cities (Oke 1987). This indicates that the average diurnal temperature rise due to urbanization may be greater than the estimated 1–3.5°C rise in temperature due to global climate change over the next 100 years (IPCC 2001).

The urban climate in temperate regions has been studied extensively, mainly in mid-latitude cities in developed countries. Fewer studies have been conducted in low-latitude, tropical climates (Arnfield 2003). Most tropical studies have dealt with urban–rural differences and fewer with microclimate variations within cities. Moreover, few studies have considered intra-urban microclimate differences in relation to urban design (Ali-Toudert 2006).

This study focuses on the influence of urban design on street-level thermal comfort. It has been carried out in two climate types common in many developing countries: hot dry and hot humid. The two cities chosen to represent these climate types are Fez in Morocco (hot dry) and Colombo in Sri Lanka (hot humid).

1.2 Problem statement

Poor outdoor thermal comfort and its consequences

In hot climates, urban warming will lead to decreased thermal comfort in urban areas. This has a negative effect on people's well-being and can have serious consequences for health; it is well known that the frequency of heat stroke and heart-disease increases with increased heat stress[1]. It is also a known fact that efficiency in the performance of both mental and physical tasks diminishes at uncomfortably high temperatures (McIntyre 1980).

However, the lack of outdoor thermal comfort has gained little attention in developing countries. Although people adapt to difficult climate conditions, this is likely to be a hidden problem, especially for the urban poor, who spend much of their time outdoors (see e.g. Correa 1989) and whose buildings are poorly adapted to the climate and thereby sensitive to urban warming.

The lack of outdoor thermal comfort is also likely to have negative social and economic consequences. If the climate is too unpleasant, people will tend to spend time outdoors only when necessary, that is, in performing essential tasks, such as travelling to work, shopping, etc. Optional and social activities – such as taking a walk, meeting people in public spaces, children's play, and so forth – will diminish (Gehl 2001, Baker et al. 2002, Givoni 2003 et al.). As a consequence, there is also a risk that outdoor commercial activities – such as cafés and restaurants, street and open-air markets, cultural events, etc. – will suffer.

Poor urban microclimatic conditions will also, indirectly, lead to deteriorating indoor comfort. This will have a negative impact on performance and health, and will also lead to increased use of air conditioning, subsequently resulting in higher energy costs for urban dwellers.

The consequences of greater energy use include increased air pollution through the consumption of fossil fuels and higher pressure on the energy supply, which may cause frequent power outages. In warm countries, there is also a risk that a feedback loop will arise: air conditioning units cool the interior of buildings but emit sensible heat to the exterior, further worsening outdoor conditions and creating a vicious circle (de Schiller and Evans 1998, Baker et al. 2002).

Lack of climate-conscious urban planning and design

Although urban areas can be designed to offer a favourable microclimate, possibly more pleasant than that of surrounding rural areas (Givoni 2003), the opposite is normally the case. A major reason for urban areas often becoming unnecessarily uncomfortable is that urban microclimate and outdoor thermal comfort are generally ascribed little importance in urban planning and design processes (Evans and de Schiller 1996, Eliasson 2000). Aynsley and Gulson (1999) interpret the lack of climate consciousness in urban planning and design as follows: *"Urban climate is often a largely unplanned outcome of the interaction of a number of urban planning activities […], an outcome for which no authority and no profession takes responsibility"*. Studies have shown that knowledge about climate issues among planners and urban designers is often missing and that there is a lack of suitable design tools for urban planners and designers (Eliasson 2000, Givoni 2003 et al.).

1 A heat wave in Europe in 2003 is believed to have caused the death of some 35,000 people (WHO 2005).

In developing countries, rapid urbanization often implies the uncontrolled growth of cities through the formation of substantial informal settlements. In these settlements, climate aspects are often disregarded.

One of the reasons that planned settlements also become uncomfortable is that regulations determining urban design are often inspired by planning ideals from temperate climates and consequently poorly suited to local conditions (see e.g. Al-Hemaidi 2001 and Baker et al. 2002).

1.3 Aim of the thesis

There is a need to find ways of improving thermal comfort conditions in tropical urban areas and of increasing the awareness of climate considerations among urban planners and designers in these cities.

The main aim of this thesis is to deepen the knowledge about the relationship between urban design, microclimate and outdoor thermal comfort in hot dry and hot humid climates through studies conducted in the cities of Fez and Colombo. The aim is also to highlight the impact of urban planning on the urban microclimate.

To achieve these research objectives, the following questions must be answered:

- How do microclimate and outdoor thermal comfort vary temporally and spatially?
- Which are the main design parameters influencing the urban microclimate and outdoor thermal comfort?
- To what extent are climate and thermal comfort issues considered in the urban planning and design processes?
- Do existing urban regulations favour or hinder climate-conscious urban design?
- How can new urban areas be designed to improve the microclimate and thermal comfort at street level?

The results of this study could provide a foundation for the development of guidelines and recommendations for climate-conscious urban design in Fez and Colombo, as well as in other cities with similar climates.

1.4 Scope and limitations

The research presented in this study concentrates on how urban design affects the microclimate and outdoor thermal comfort. The study is limited to the microclimate at street level, i.e. the *urban canopy layer*, roughly the space between the ground and the roof tops.

The study is limited to two cities, one in a hot dry climate and the other in a hot humid climate. The intention has not been to compare the two cities. Although some of the findings are general, the conclusions of the study are not necessarily valid throughout the hot dry and hot humid climate groups, since there are climate variations within each of these and considerable variations between different cities in terms of size, planning principles, proximity to the sea, topography, etc.

The main focus is on residential and mixed-use areas and, to a lesser extent, on other land use areas. The study concentrates on urban design and the detailed planning level rather than on comprehensive planning aspects, such as the location of urban areas within a city. The study is limited to street design and does not include public spaces such as squares and parks. Vegetation is studied only for shading purposes.

The cities studied contain both "traditional" and "modern" urban forms. These differ not only physically but also relate to differences in culture and lifestyle. Here, however, urban form is dealt with strictly in regard to its geometrical features.

Thermal comfort is estimated by calculating a comfort index based on environmental parameters that are either measured, calculated or simulated. The study does not include field studies on subjective thermal comfort as perceived by pedestrians.

The amount of air pollution is affected by urban geometry. However, air pollution and its consequences on health are not treated here. Moreover, the effect of air pollution on thermal conditions in cities has proven to be small, at least in moderately polluted cities, such as those included in this study.

The effect of anthropogenic heat is not considered in this study as its effect on the urban climate has been found to be negligible in most cases. Energy use in buildings is not treated, mainly to limit the study but also because the use of space conditioning is, to date, limited in both of the cities studied. Although indirectly affected by the urban climate, indoor thermal comfort is not treated.

1.5 Structure of the thesis

This thesis consists of a summary and four annexed journal papers. The thesis summary is mainly based on the papers but also includes the results of a study of urban regulations and the consideration of climate aspects in urban planning and design.

Chapter 2 provides background on the two cities, Fez and Colombo, and on urban design regulations in each city. Chapter 3 defines general concepts regarding the characteristics of the urban climate as well as outdoor thermal comfort. Chapter 4 is a review of literature relevant to urban climate, outdoor thermal comfort and climate-conscious urban design in tropical climates. Chapter 5 presents the different research methodologies and techniques applied in this study. Chapter 6 contains the results of microclimate measurements and simulations, calculations of thermal comfort, as well as the role climate aspects play in the urban planning process. The interpretations and implications of the results are discussed in Chapter 7.

The thesis includes the following papers:

I Johansson, E.: Influence of urban geometry on outdoor thermal comfort in a hot dry climate: A study in Fez, Morocco. *Building and Environment*, 2006, vol. 41, no. 10, pp. 1326–1338.

This paper deals with microclimate measurements and the calculation and analysis of outdoor thermal comfort conditions in the city of Fez during the winter and summer seasons.

II Emmanuel, R., and Johansson, E.: Influence of urban morphology and sea breeze on hot humid microclimate: the case of Colombo, Sri Lanka. *Climate Research*, 2006, vol. 30, no. 3, pp. 189–200.

This paper deals with microclimate measurements and the analysis of the effect of urban design and sea breeze on microclimate in the city of Colombo during the inter-monsoon period in April–May.

III Johansson, E., and Emmanuel, R.: The influence of urban design on outdoor thermal comfort in the hot, humid city of Colombo, Sri Lanka. *International Journal of Biometeorology*(in press).

This paper treats the calculations of outdoor thermal comfort in the city of Colombo based on the measurements presented in paper II. The role of urban design and sea breeze on outdoor thermal comfort is analyzed.

IV Johansson, E.: Simulations of urban microclimate and outdoor thermal comfort in the hot dry city of Fez and in the hot humid city of Colombo. *Manuscript*.

This paper presents simulations of microclimate and outdoor thermal comfort in the cities of Fez and Colombo and includes proposals for optimized design solutions for different seasons.

In papers II and III, the implementation of the study, analysis of results and composition were conducted in cooperation between the authors.

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2 Cities studied

This Chapter explains why the cities of Fez and Colombo were chosen for this study and provides background information on the two cities regarding their historic development and current urban structure as well as a brief overview of the urban planning process and a more detailed description of the urban design regulations in force.
A glossary of terms and definitions is given in Appendix 1.

2.1 Choice of cities

The cities were selected as a result of both deliberate choice and practical considerations. The aim was to find two cities in developing countries located in different climate zones. Another requirement was the population size of the cities. Very large cities such as mega-cities may have high levels of anthropogenic heat influencing the urban climate. Conversely, cities that are too small may present a limited variation in urban design and therefore limited intra-urban microclimatic differences. The choice was, however, also a result of local contacts and on-going research cooperation[1] which facilitated the implementation of the study.

The cities chosen for this study, Fez in Morocco and Colombo in Sri Lanka, represent two types of climate typical of many urban areas in developing countries. Fez is situated in the hot, dry climate of North Africa, whereas Colombo belongs to the hot, humid climate of South Asia (Fig. 2.1). The intention has not been to compare the two cities, rather, they were chosen to represent two climate types in which a large part of the developing world's population lives.

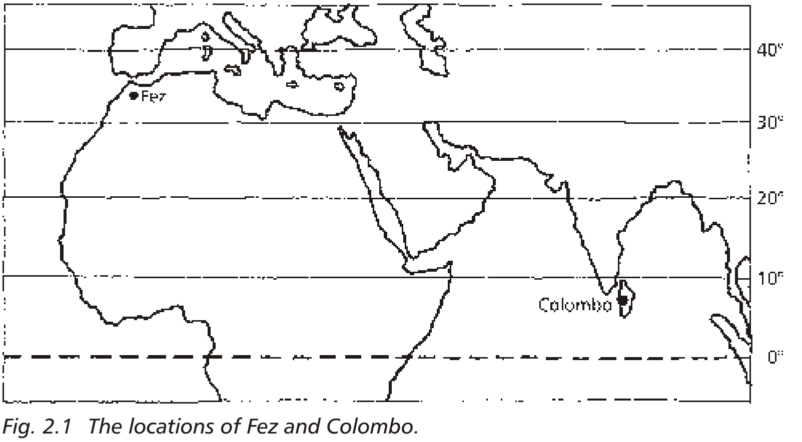


Fig. 2.1 The locations of Fez and Colombo.

1 The institutes cooperating in this study were the Moroccan Laboratoire Public d'Essais et d'Etudes (LPEE) and the Sri Lankan Department of Architecture, University of Moratuwa.

Hot dry climates are found at latitudes between approximately 15° and 35° north and south of the equator (Koenigsberger et al. 1974, Evans 1980). They are characterised by distinct seasons: a long hot and dry season and a shorter wet or cool season. The dry season is characterised by high daytime temperatures, low humidity and sparse precipitation. Mean daytime maximum temperatures vary between about 32°C and 45°C depending on the region. Vapour pressure varies between 7.5 and 15 hPa. As a result of low humidity and clear skies, solar radiation is intense and nocturnal cooling high, resulting in large diurnal temperature fluctuations, often exceeding 15°C. Some hot dry regions have mild winters with a short wet season, while others, such as Fez, have a cold season with higher precipitation and temperatures near the freezing point at night (Fig. 2.2a). Hot dry climates are typically found in North Africa, the Middle East, parts of Central Asia, central Australia and in parts of North and South America.

Hot humid climates are found between latitudes approximately 20° north and south of the equator (Koenigsberger et al. 1974, de Schiller and Evans 1998). In the region close to the equator, where Colombo is situated, annual temperature variations are small (Fig. 2.2b). Further from the equator, towards the sub-tropical zone, hot humid conditions may be found during the summer season. The hot humid climate is characterised by high average temperature and humidity. Mean daytime maximum temperatures vary between 27 and 32°C depending on the region. Vapour pressure varies between 17.5 and 30 hPa. Precipitation is high, but often varies between wetter and dryer seasons as a result of the monsoon winds. Due to high humidity and relatively high cloud cover, both daytime solar radiation and nocturnal cooling are reduced, resulting in low diurnal temperature ranges, often below 10°C. Since the hot humid tropics lie within

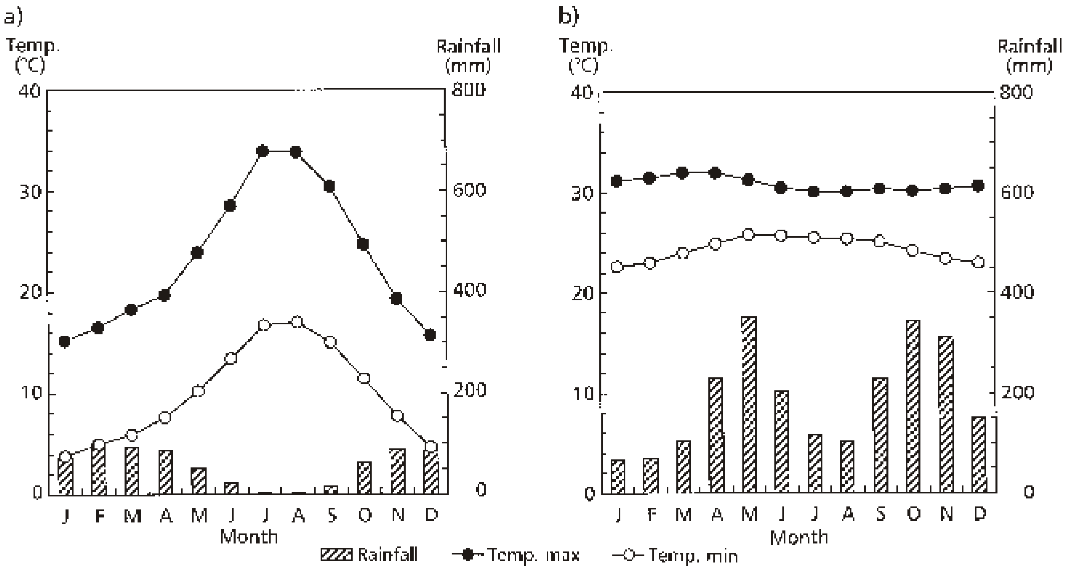


Fig. 2.2 *Mean maximum and minimum temperatures as well as rainfall in (a) Fez (based on data from Fez airport at 33°58'N, 4°59'W, altitude 571 m) and (b) Colombo (based on data from Colombo city meteorological station at 6°54'N, 79°52'E, altitude 7 m).*

the Inter-Tropical Convergence Zone, wind speeds are normally low. Hot humid climates are typically found in Western and Central Africa, South and South-East Asia, Northern Australia, the Caribbean, Central America and the northern part of South America.

2.2 Fez

The city of Fez (34.0°N, 5.0°W) is located in the interior of Morocco in a valley at an altitude of about 400 m between the Rif mountains to the north and the Atlas mountains to the south. Intra-urban altitude differences are well above 100 m. Fez has distinct seasonal variations with hot, dry summers and fairly cold and wet winters (Fig. 2.2a). Diurnal temperature fluctuations are large, especially in the summer. Due to the limited amount of rainfall, the city has little green cover, few green areas, and is surrounded by sparse vegetation. See also Paper I.

Morocco (2006 estimates)	
Population	31.5 million
Population density	70 inhab./km^2
Annual growth rate	1.48%
Urban population	18.5 million (59%)
Urban growth rate	2.7%
Major cities	Casablanca (3.2 million)
	Rabat-Salé (1.6 million)
	Fez (1.0 million)
	Marrakech (0.9 million)

Sources: UN (2006), World Gazetteer (2006).

Historic development

The city of Fez was founded following Arab conquests in North Africa. The first settlers arrived in the 8th century and the city was established in the following century. When the Marinids arrived in the late 13th century, they extended the city and made Fez the capital of Morocco. In the 15th century, Fez had become a commercial and cultural centre and had relations with Europe, Sub-Saharan Africa and the Middle East (Ichter 1979). The city was built according to Arab-Islamic urban design principles with courtyard houses and narrow, winding alleyways (Figs. 2.3a and 2.4a). Fez remained the cultural, economic and spiritual centre of Morocco until 1912 when most of present-day Morocco became a French protectorate. The city, which had been the largest in Morocco, then lost much of its economic importance, since the French chose Rabat as the capital of the protectorate.

In the 1920s the New city (*Dar Debibagh* or *Ville nouvelle*) was founded on a plateau southwest of the walled Medina (Fig. 2.9). The new city was built in a "colonial" style[2] and exclusively housed Europeans. Its main streets consisted of wide avenues in a regular grid

2 The plan was conceived by the French urban planner Henri Prost, who planned several colonial cities in Morocco during the first decade of the protectorate.

Fig. 2.3 (a) A street in the Medina and (b) an avenue in the colonial part of the new city.

pattern (Fig. 2.3b). The local population continued to live in the Medina (the old city), which was left fairly intact by the French (Vacher 1991). Towards the end of the period of the French protectorate, the Ain Kaddous[3] district was planned on the hillside northwest of the Medina (Fig. 2.9). This district, which was built to release the population pressure on the Medina, consisted largely of "modern" residential blocks and became a dormitory city for low and middle-income groups (Bianca 2000). However, some parts of Ain Kaddous were built with "neo-traditional" multi-family courtyard houses intended for low-income residents.

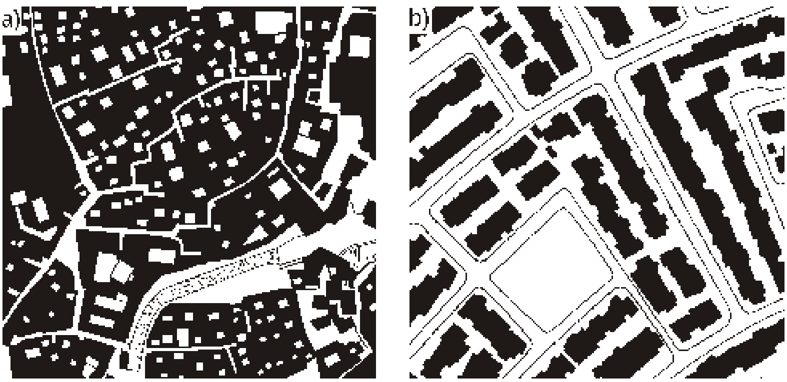


Fig. 2.4 Footprint area of buildings and road network in (a) the core of the historical Medina (Seffarine district) and (b) a residential suburb in the new city (Adarissa district). Map size: 200 m × 200 m.

Morocco's population grew rapidly towards the end of the colonial period and this growth accelerated during the initial decades following Morocco's independence in 1956 (Abu-Lughod 1980). This resulted in rapid urbanisation, which has continued to the present day (Fig. 2.5). The planned extensions of the city were primarily to the

3 The district was planned by Michel Ecochard, who was the chief planner in Morocco at the end of the protectorate (1945–53).

south and southwest, as a continuation of the colonial city, and to the north (Ain Kaddous). The former consisted primarily of European style construction in the form of low-density residential areas (Figs. 2.4 and 2.6), while the latter consisted of low and middle-income settlements (Fig. 2.7a). The growth rate reached its peak during the 1980s and resulted in an increase in informal settlements, which grew up to the east and southeast of the Medina, in parts of Ain Kaddous and around the new city. The informal sector includes illegal, spontaneous settlements, illegally extended buildings, rural building types and shanty towns (Ichter 1979) (Fig. 2.7b).

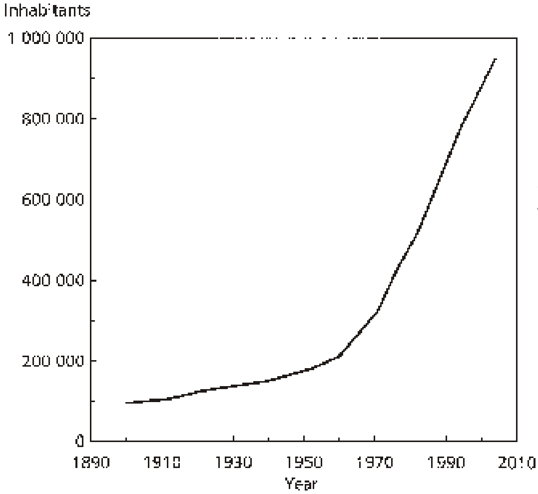


Fig. 2.5
Population growth in the city of Fez between 1900 and 2004. During this period, the city's area increased substantially.

Sources: Bouayad (1979), Abu-Lughod (1980), Laborie (1990), HCP (2004).

Fez and other major Moroccan cities faced increasing housing shortage problems due to rapid urbanisation in the 1980s and 1990s. To improve the situation, the national 200,000 Dwellings Programme was initiated in the mid-1990s. Moreover, the urban codes, many of which dated back to the protectorate, were revised slightly.

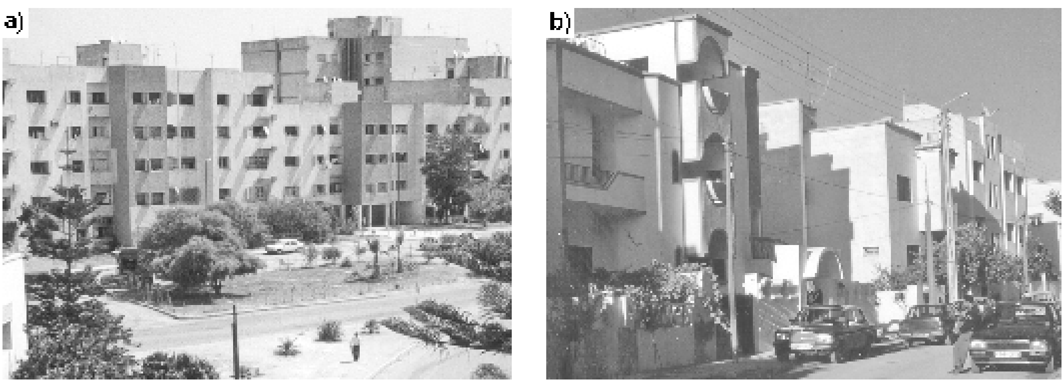


Fig. 2.6 Residential buildings in the Adarissa district on the southern outskirts of the new city. (a) Apartment buildings and (b) terraced houses.

Current situation

Annual urban growth in Fez, between the censuses of 1994 and 2004, was 2.1% and, despite local and national efforts to increase low-income housing production, the city has not managed to provide adequate housing for the increasing number of low-income residents. The consequences have been overcrowding in the old Medina, mainly involving rural migrants, and the creation of a number of informal low-income settlements, often situated on rough terrain. In 2000, an estimated 17% of the population[4] was living in the informal sector, either in illegal settlements or in shanty towns.

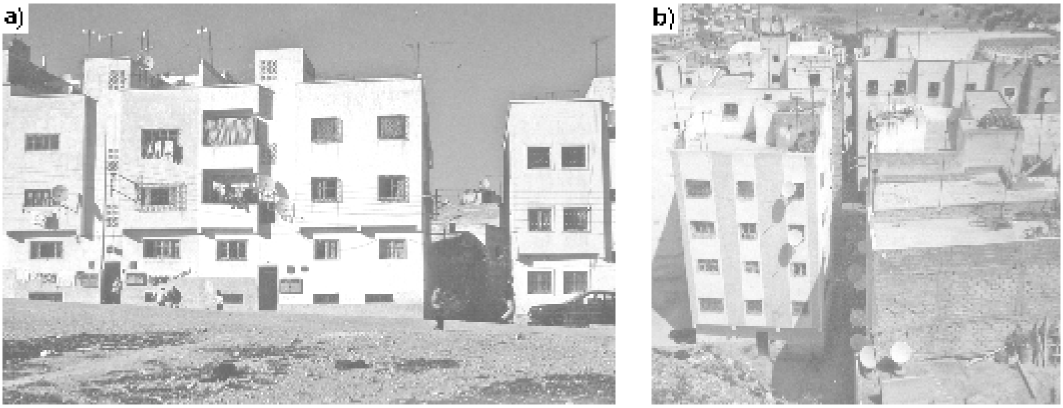


Fig. 2.7 Low-income settlements in Ain Kaddous: (a) neo-traditional courtyard houses (Hay Benzakour district) and (b) an illegal settlement (Hay Hassani district).

Another problem in Fez is the uneven distribution of the population. Low-income residents in parts of the Medina and the informal sector live in very high population densities, which stand in stark contrast to the much lower densities of the formal sector found in the new city. In the late 1970s, the Medina is believed to have had an average population density of nearly 1,000 inhab./ha, whereas the densities of Ain Kaddous and the new city were 350 and 55 inhab./ha respectively (Bouayad 1979, Ichter 1979)[5].

The failure to provide housing for the urban poor has been a major concern among the national authorities in recent years (Tahiri 1999, MHU 2005). In an attempt to review current urban regulations and reduce all forms of unsanitary housing, a new law aimed at guaranteeing sufficient low-income housing and simplifying building permit procedures was proposed in 2004 (MHU 2006). A complete revision of urban regulations that is to result in a national Urban Planning Code (*Code de l'Urbanisme*) is currently under preparation.

The recent debate has also involved the type of low-income housing established nationally by the decree of 1964, which is still in

4 This figure, which does not include the people living in overcrowded parts of the Medina, is based on population data by Observatoire de l'Habitat (2001) and CERED (2004).

5 However, since the 1981 declaration of the old Medina of Fez as a World Heritage site, one aim has been to reduce its population density and the current density is estimated at 550 inhab./ha. (Carfree.com 2006)

force. This type of housing consists of the neo-traditional courtyard houses, mentioned previously, laid out on a regular grid plan[6]. In recent years, this has been criticised for causing low population density (Tahiri 1999) and for its lack of cultural adaptation – the size and distribution of the rooms being inappropriate and the courtyard not being located at the centre of each housing unit as in traditional housing (Pinson 1994). An on-going study (MHU 2005) aims to revise the regulations for low-income housing in order to increase density and reduce costs.

Urban design regulations

Morocco is divided into regions, each of which is divided into provinces and prefectures. Each province/prefecture is divided into rural and urban communes (the latter sometimes called municipalities). The city of Fez belongs to the Fez-Boulemane region, which has 1.6 million inhabitants and covers 20,000 km^2 (Fig. 2.8). This region is subdivided into three provinces and the Prefecture of Fez, which, in turn, consists of two municipalities and three rural communes.

In Morocco, regional and urban planning is governed by "urban agencies" (*agences urbains*), which serve under the Ministry of Regional and Urban Planning, Housing and Environment[7]. Each of the regions in Morocco has one or more urban agencies. The city of Fez

Fig. 2.8 Northern Morocco and the region of Fez-Boulemane.

6 This type of housing was originally introduced at the end of the protectorate by Michel Ecochard, the chief planner in Casablanca at the time, on an 8 m by 8 m grid known as la trame Ecochard.

7 MinistPre de l'aménagement du territoire, de l'urbanisme, de l'habitat et de l'environnement.

is covered by the Agency of Urban Planning and Preservation of Fez[8] (AUSF), which was founded in 1991. AUSF is responsible for the coordination of all planning issues for the entire region of Fez-Boulemane. AUSF's mission comprises urban planning (including the establishment and implementation of the master plan, as well as the establishment of urban regulations), urban management and technical assistance to the rural and urban communes/municipalities within the region regarding urban planning issues (AUSF 2006).

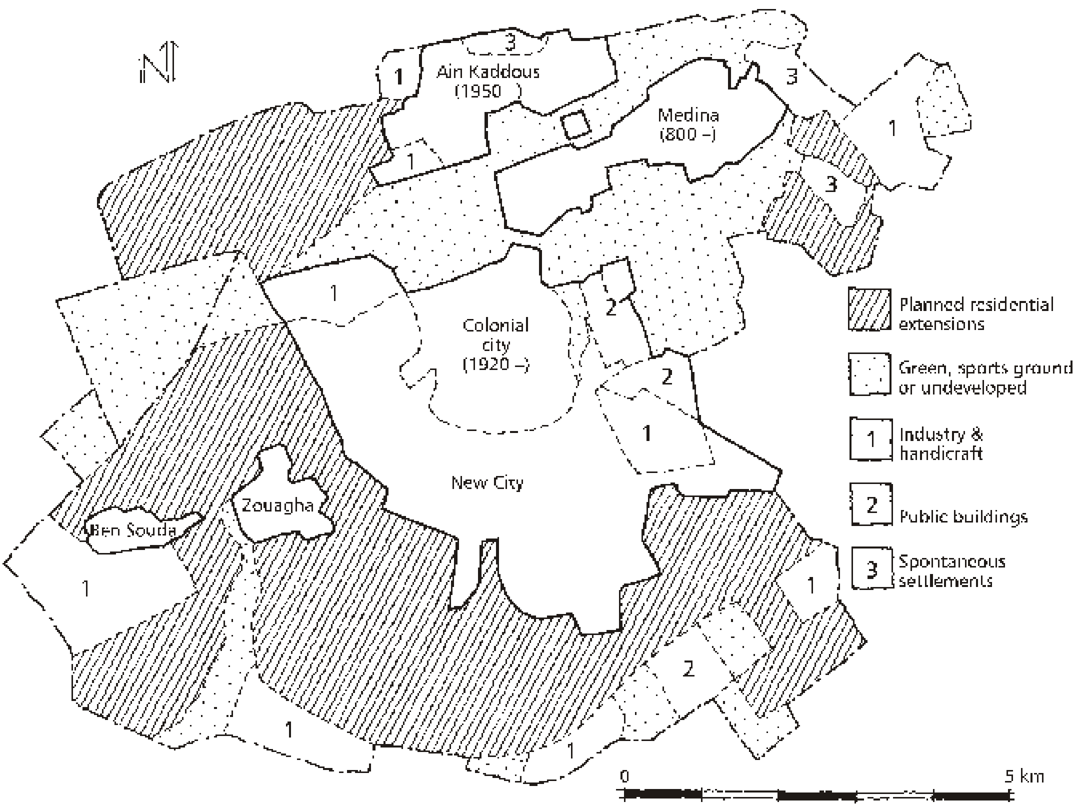


Fig. 2.9 The city of Fez and its three main parts: the old city (the Medina), the new city and Ain Kaddous. The planned extensions according to the current master plan of 1991 are also shown.

Source: The master plan of Fez, Agence Urbaine et de Sauvegarde de Fès.

Urban planning in Fez is governed by two regulatory documents. At a comprehensive level, urban areas are covered by a master plan (*Schéma Directeur d'Aménagement Urbain*), comprising land-use and zoning maps, as well as a written report explaining the aims of the plan and describing how to implement it. At a detailed level, land use plans (*Plan d'Aménagement*) cover a whole or part of a municipality or an urban centre. The master plan, which is valid for a maximum of 25 years, determines, among other things, new zones of urbanisation, the dates when developments are planned to start, the location of different land-use zones and planned population densities within residential zones. The current master plan, which origi-

8 Agence Urbain et de Sauvegarde de Fès.

nates from 1980 but was revised in 1991, is shown in Fig. 2.9. Its goals include the provision of 150 hectares of new urban land per year, half of which is reserved for housing. The urban extensions are planned both as an extension of the city to the west, southwest and south as shown in Fig. 2.9 and as the development of urban centres outside the main urban area (AUSF 2006).

Land-use plans are valid for ten years, with the exception of zoning regulations which may be valid longer. These plans define different land-use zones (residential, industrial, etc), the road network, green areas, preservation of historical monuments, etc. and contain specific rules pertaining to urban form.

Urban zones

The land-use plans for Fez divide the municipal area into zones of different types of development. The existing urban zones are shown in Table 2.1. Many of the zones are divided into sub-zones, as can be seen in Table 2.2 and Table 2.3. Basically, these urban zones can be found throughout the city, except zone M, which is unique to the old city. However, zones A and B are mainly found in the city centre, i.e. basically the colonial part of the new city. To the west, southwest and south of the city centre the residential zones C, D and E are dominant.

Table 2.1 Urban zones and development types in Fez (AUSF 1988, 2006).

Zone	*Land use*	*Description*
A	Mixed	Attached apartment buildings for residential use, business, offices, public administration and hotels (city centre)
B	Mixed	Attached apartment buildings for residential use, business, offices, handicraft, public administration and hotels
C	Residential	Detached apartment buildings for residential use, but also commercial activities, offices and hotels
D	Residential	Detached, semi-detached and terraced houses ("villas") intended mainly for residential use
E	Residential	Neo-traditional courtyard buildings on small plots for low-income residents
In	Commercial	Buildings for industrial, commercial, handicraft and office use
S	Special	Residential or non-residential buildings subject to special conditions
M	Old city (mixed)	Mainly traditional courtyard houses, intended for a variety of activities

Regulation of urban form

The urban codes dealing with urban form constitutes parts of the land-use plans. The city of Fez has two regulations that are in force: the "General Regulations for the Land Use Plan of the Wilaya of Fez[9]" (AUSF 1988) and the "Regulations for the Land Use Plan of the Walled Medina of Fez" (AUSF and ADER-Fès 1999). The former of

9 Wilaya means administrative region. The former Wilaya of Fez did not include the Province of Boulemane, but this province is now also covered by the regulation.

these documents concerns all urban areas except the historical Medina; it has been subjected to some minor revisions lately (AUSF 2006). The latter regulation concerns the historic old city (the Medina). In addition to these codes, the old by-law "Regulation of Road Network and Building" (Ville de Fès 1969) is still in force.

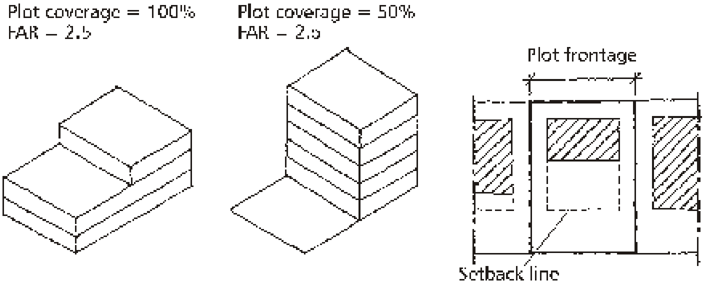


Fig. 2.10 Illustration of plot coverage, FAR, plot frontage and setbacks.

In Fez, the new city has the greatest variety of building types comprising street-aligned attached apartment buildings (zones A and B), detached apartment buildings (C), detached low-rise houses (D) and neo-traditional courtyard houses for low-income residents (E). The rules governing the number of storeys, building heights, distances between buildings, plot coverage, floor area ratio (FAR)[10], setbacks, etc. are shown in Table 2.2. Plot coverage, FAR, plot frontage and setbacks are illustrated in Fig. 2.10.

As can be seen in Table 2.2, maximum building height is related to street width. The maximum FAR varies between only 0.2, for the largest detached houses (*villas*) in zone D5, up to 2.4 for four-storey attached apartment buildings in zone B3 (for buildings of more than four storeys, there are no FAR limitations). There are extensive variations in minimum plot sizes: from 60 m^2 for low-income housing (zone E) to 4,000 m^2 for the most luxurious category of detached houses (zone D5). Similarly, plot coverage varies between only 10% for detached houses (zone D5) to 80% for low-income housing (zone E1). There are no setback rules for apartment buildings in the city centre and low-income courtyard houses. However, detached apartment buildings and low-rise buildings have minimum front, back and side setbacks. For street-aligned buildings (zones A, B and E), projected upper floors are permitted above a height of 2.2 m (Ville de Fès 1969).

In the Medina (zone M), new construction is rare and mainly takes the form of infill buildings in existing built-up areas. Consequently, regulations differ completely from those applied in the new city. The Medina has basically three types of buildings: old historical buildings – residential, commercial and public – (zone M1), more recently constructed neo-traditional buildings (M2) and modern residential blocks (M3). There are also neo-traditional courtyard houses for low-income residents (E2) and a zone of modern commercial and industrial buildings (IM). See Table 2.3.

10 FAR is calculated as the total floor area of a building divided by the total area of the plot (Acioly and Davidson 1996).

Table 2.2 The regulations pertaining to urban form in the city of Fez (not including industrial buildings and buildings in the historical Medina). FAR = floor area ratio, H = building height, W = distance between buildings.

Zone	Type of building	Type of use	Plot size (m^2)	Min. plot frontage (m)	Max. FAR	Max. plot coverage (%)	Max. no. of floors	Max. H (m)[a]	Minimum setbacks front (m)	rear (m)	side (m)
A1	Apartment building	Residential/ commercial	no limit	no limit	no limit	no limit	7[b]	24 or 1.5 W	—	0.5 H or 4	—
B1	Apartment building	Residential/ commercial	≥ 250	10	no limit	no limit	6[b]	21 or 1.2 W[c]	—	0.5 H or 4	—
B2	Apartment building	Residential/ commercial	≥ 250	10	no limit	no limit	5[b]	17.5 or 1.2 W[c]	— —	0.5 H or 4	—
B3	Apartment building	Residential/ commercial	≥ 200	10	2.4[d]	70	4[b]	14.5 or W	—	0.5 H or 4	—
B4	Apartment building	Residential/ commercial	≥ 200	10	2.0	70	3[b]	11 or W	—	0.5 H or 4	—
B5	Apartment building	Residential/ commercial	≥ 120	8	1.6	60	3[b]	11 or W	—	0.5 H or 4	—
C1	Apartment building	Residential, hotel	≥ 5000	50	1.4	30	5[b]	17.5 or W	5	0.5 H or 6	0.5 H or 6
		Office	≥ 2000	40							
C2	Apartment building	Residential, hotel	≥ 5000	50	1.2	35	4[b]	14.5 or W	5	0.5 H or 6	0.5 H or 6
		Office	≥ 2000	40							
C3	Apartment building	Residential, hotel	≥ 5000	50	1.0	40	3[b]	11 or W	5	0.5 H or 6	0.5 H or 6
		Office	≥ 2000	40							
D1	Terraced houses	Residential	≥ 200	10	1.0	50	2	8	5	4	—
	Semi-detached h.		≥ 300	15	0.8	40	2	8	5	4	4
D2	Detached houses	Residential	400–999	20	0.6	30	2	8	5	4	4
D3	Detached houses	Residential	1000–1999	25	0.5	25	2	8	5	6	6
D4	Detached houses	Residential	2000–3999	25	0.3	15	2	8	8	8	8
D5	Detached houses	Residential	≥ 4000	50	0.2	10	2	8	8	8	8
E1	One-family courtyard	Residential	≥ 60	6	1.6	80	2	8	—	—[e]	—
E2	Multi-family courtyard	Residential	≥ 80	8	2.2	75	3	11	—	—[f]	—

a Parapets for trafficable flat roofs of a maximum of 1.2 m are permitted above this height.
b Additional storeys are permitted, provided a light angle of 45° towards the street is maintained and the maximum building height (H) is respected.
c If W ≤ 15 m.
d For apartments buildings of ≥ 100 m^2 there is no FAR limit.
e Min. courtyard size = 12 m^2, min. courtyard width = 3 m.
f Min. courtyard size = 20 m^2, min. courtyard width = 4 m.

Table 2.3 gives maximum building heights for the old city, although actual height may not exceed that of existing, adjacent buildings. Only in zone E2 is maximum FAR limited, at 2.2. Plot coverage for all zones is maximised to 75% (guaranteeing that the courtyard occupies at least 25% of the plot). There are no setback rules; on the contrary buildings should be street-aligned and attached on all other sides.

Table 2.3 Regulations pertaining to urban form in the historical Medina of Fez (not including industrial buildings). FAR = floor area ratio, H = building height, W = distance between buildings.

Zone	Plot size (m^2)	Min. plot frontage (m)	Max. FAR	Max. plot coverage (%)	Max. no. of floors	Max. H (m)	Min. W (m)	Minimum courtyard size	Minimum courtyard width (m)
M1	< 100	—		75	3	14[a]	—	25%	3
	≥ 100								5
M2	< 100	—		75	3	13[a]	—	25%	3
	≥ 100								5
M3	< 100	—		75	2	9	—	25%	3
	≥ 100								5
E2	≥ 80	8	2.2	75	3	12.2[b]	H	20 m^2	4

a Building height should, however, not exceed that of adjacent buildings.
b Including the parapet wall. Not including the parapet, the max. height is 11 m.

Areas studied

In this study, urban microclimate and outdoor thermal comfort were studied in detail in one neighbourhood belonging to zone D1 (semi-detached and terraced houses) in the new city and in one neighbourhood with buildings of type M1 in the historical Medina. The positions of the measurement sites are shown in Fig. 5.1. An analysis of the consequences of urban regulations on outdoor thermal comfort is given in Section 6.4.

2.3 Colombo

The city of Colombo (6.9°N, 79.9°E) is located on Sri Lanka's west coast. It has a flat terrain with the lowest areas (some being marshland) lying just below sea level and the highest points at 18 m above sea level (van Horen 2002). The climate is constantly hot and humid with a few rainy seasons. The combination of high temperature and humidity results in considerable heat stress, especially during the daytime. Due to abundant rainfall, Colombo is to a large extent a very green city and is surrounded by marshlands, paddy fields and rubber estates. See also Papers II and III.

Sri Lanka (2006 estimates)	
Population	20.7 million
Population density	316 inhab./km^2
Annual growth rate	0.88%
Urban population	4.4 million (21%)
Urban growth rate	0.8%
Major cities	Colombo* (0.6 million)
	Dehiwala-Mt. Lavinia (0.2 million)
	Moratuwa (0.2 million)
	Jaffna (0.2 million)

**Colombo Municipal Council*

Sources: UN (2006), World Gazetteer (2006).

Historic development

Colombo is believed to have first been settled in the 8th century in what is now the Pettah district. Due to its harbour, the city grew to become an important commercial centre in the 13th century (UDA 1999a). In the early 16th century, Colombo came under colonial rule, beginning with the Portuguese, followed by the Dutch and ending with 150 years of British rule, which ended in 1948[11]. It was in 1815, during the British colonial period, that Colombo became the capital city and began to expand to the north, east and south. The British introduced a legal and regulatory system that, to a large extent, is still in use (van Horen 2002).

The oldest parts of the city are the old commercial quarters (Pettah) and the old colonial city centre (Fort). The former is characterised by street-aligned, medium rise buildings of 3–4 storeys and narrow streets (Figs. 2.11a and 2.12a). The latter has street-aligned colonial buildings laid out in a grid with fairly wide streets (Fig. 2.12b). The three to four-storey buildings have high ground floors with pedestrian arcades (Fig. 2.11b). The areas that were developed outside the historic core became very different from the centre. Colombo's first city plan was adopted in 1921 with the aim of creating a garden city[12]. The plan was never fully implemented, but included the Cinnamon Gardens, today a low density, high-income neighbourhood characterised by a high level of greenery and its tree-lined streets (UDA 1999a). At the end of the colonial period, the "Abercrombie Plan"[13] was developed with the aim of decentralising the economic activities of the city by creating satellite towns around the

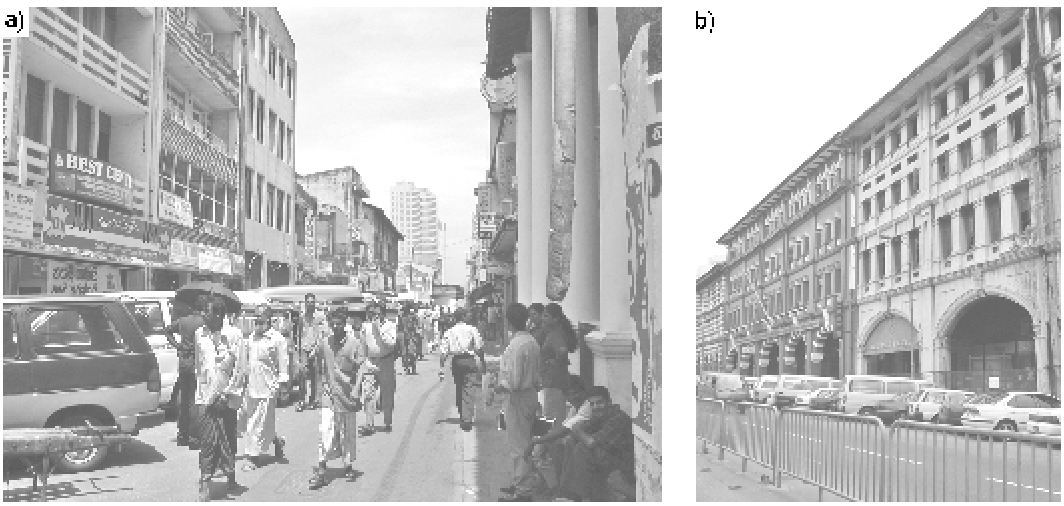


Fig. 2.11 (a) Street in the old commercial quarters of Pettah and (b) colonial buildings in Fort.

11 Whereas the Portuguese and Dutch only had control of the major coastal cities, the British colonised the entire island of Ceylon in 1815.

12 The plan was prepared by the British urban planner Sir Patrick Geddes.

13 Prepared by the British urban planner Sir Patrick Abercrombie, who formulated the Greater London Plan of 1945.

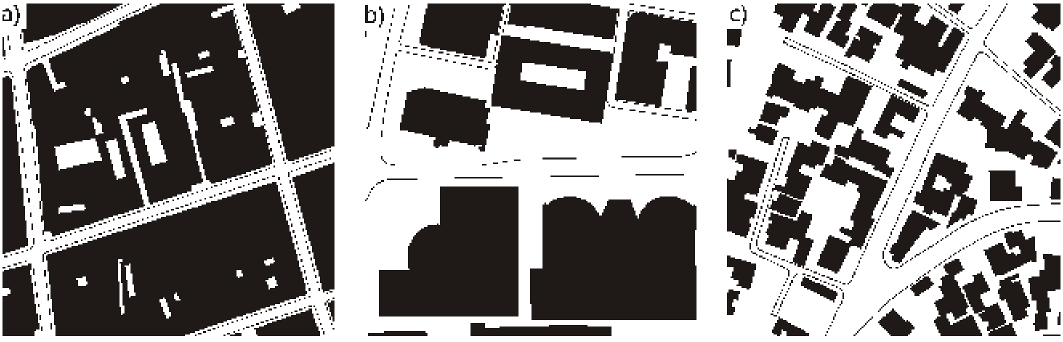


Fig. 2.12 Footprint area of buildings and road network in (a) the old commercial quarters (Pettah), (b) the central business district (Fort) and (c) a residential suburb (Nugegoda). Map size: 200 m × 200 m.

city of Colombo. However, only a few of the satellite towns planned were actually built (UDA 1999a).

After Sri Lanka's independence in 1948, Colombo continued to grow and reinforce its position as the country's major urban area. Economic growth was accompanied by rapid urbanisation (Fig. 2.15). Due to the natural limits to the west (the Indian Ocean) and the east (extensive marshlands), the urban area grew primarily in a north-south direction along the national highways. The urban fabric of Colombo has, to a large extent, been characterised by low-rise (single to four-storey) buildings, wide streets and high amount of green cover (Figs. 2.12c and 2.13). In the 1960s and 1970s, problems of urban sprawl had become severe. A master plan for Colombo was completed in 1978 with the aim of achieving a more balanced spatial development, although this was never successfully implemented (van Horen 2002). However, the master plan did lead to the establishment of the Urban Development Authority (UDA), which remained the main national planning authority until the creation of the National Physical Planning Department in 2003[14].

Economic reforms at the end of the 1970s led, among other things, to a shift in housing policy. The Colombo Development Plan was produced by the UDA in 1985 and included zoning and building regulations for the city. The plan also proposed the transformation of the state to an "enabler" rather than a "provider" of housing. This new strategy was used in the Million Houses Programme (1984–1989) and the 1.5 Million Houses Programme (1990–1994) (van Horen 2002). The new strategy also included the shift from rigid master planning to a more performance-based strategy. This is reflected both in the Colombo Metropolitan Region Structural Plan of 1998 and in the City of Colombo Development Plan (UDA 1999a). The former takes into account the entire Colombo Metropolitan Region, which had 5.3 million inhabitants in 2001 (Fig. 2.14).

Increased foreign investment since the end of the 1970s has led to the transformation of the southern part of the colonial Fort area into a central business district with the construction of high-rise buildings such as the twin towers of the World Trade Centre (van Horen 2002).

14 This department will deal with planning on a broader, national scale.

Fig. 2.13 (a) The coastal Galle Road, the main north-south transport axis and (b) a street in the residential suburb Nugegoda.

Current situation

Many of the problems in Colombo are related to urban growth (Fig. 2.15) and the high number of informal settlements. Although urbanisation in Sri Lanka is low compared to many other Asian countries[15], the city of Colombo and its suburbs, where most urbanisation has taken place, have not managed to provide housing for the urban poor. In recent decades, annual urban growth of the Colombo Municipal Council has been only 0.4% (between 1981 and 2001), although during this period, the neighbouring urban areas have also grown, leading to a much larger urbanised region. The area defined by UDA as the Colombo Core Area (Fig. 2.14) had a population of about 1.1 million inhabitants in 2001.

A major concern for the authorities is that the city's growth mainly involves horizontal expansion with low-rise housing, causing several problems (UDA 1999a). This makes it more expensive to provide infrastructure and urban services, such as water supply, sewerage and drainage. Moreover, land suitable for building is insufficient (encroachment into ecologically sensitive marshlands and flood-prone lowlands is causing a number of environmental problems). However, according to the UDA (1999a), available, developable land is under-utilised – and inappropriately distributed. More than half of the city's population is estimated to live in densely populated slums[16] and shanty towns, often located on marginal land occupying only 11% of the area of the Colombo Municipal Council.

In 1997, population densities within the Colombo Municipal Council varied between below 100 persons/ha in high-income areas to 300–400 in a few high-density areas. A survey of floor-space distribution in Colombo revealed that the average plot coverage was around 43% and the average floor area ratio (FAR) was less than one. This is evidence of a dispersed city with poor land-use efficiency (UDA 1999a).

15 According to official statistics the urban population is around 20%, but according to Mendis (2003) a more realistic figure is around 30%.

16 Here, "slum" refers to old tenements in very poor condition and lacking basic sanitary facilities.

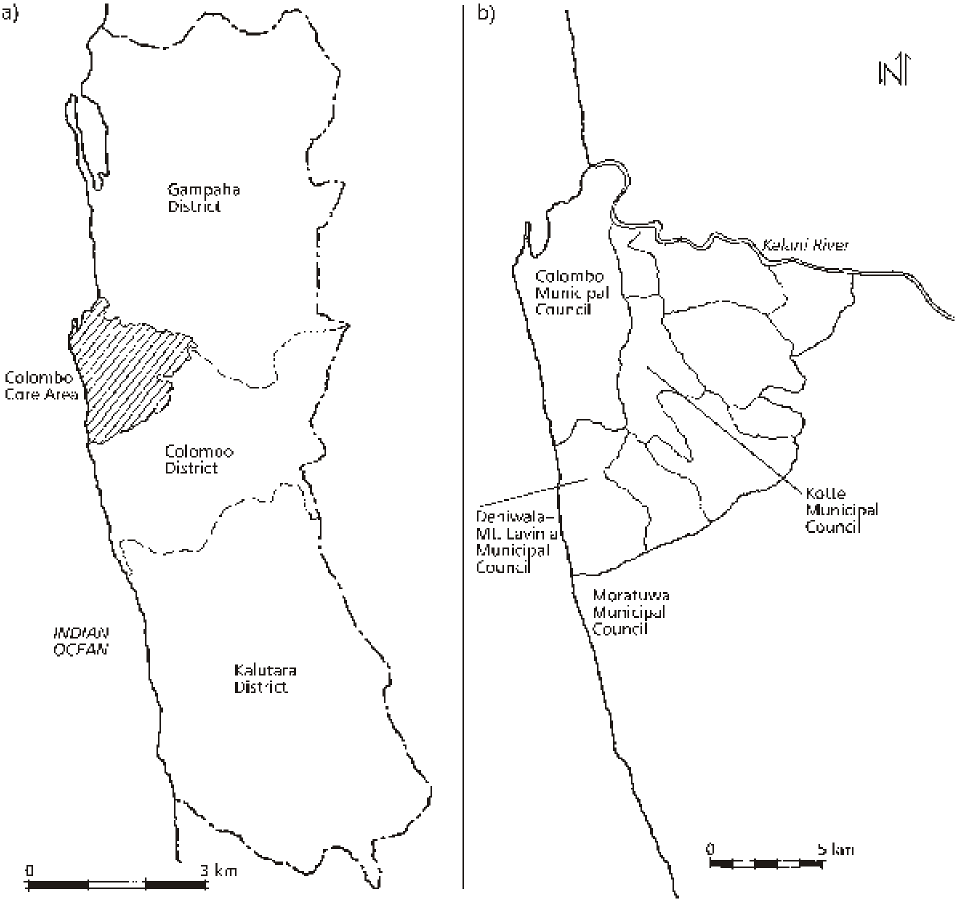


Fig. 2.14 (a) Colombo Metropolitan Region (Western Province) and its three districts. (b) Colombo Core Area consisting of the Colombo Municipal Council and neighbouring urban councils.

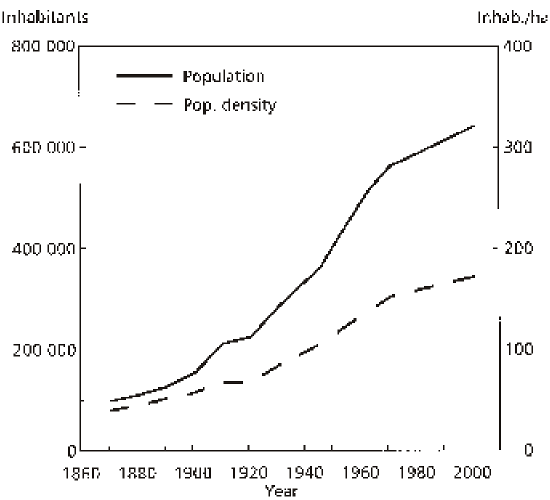


Fig. 2.15 Population growth and density of the Colombo Municipal Council (CMC) between 1861 and 2001. During this period the area of of the municipality increased from about 2500 ha to 3700 ha.

Source: UDA (1999a), Dept. of Census and Statistics (2005).

The objective of the recently issued Colombo Development Plan (UDA 1999a, b) is to reduce the expansion of slums and shanty towns and to provide housing for an increasing urban population without increasing the area designated for residential buildings. The plan is to increase population densities by radically increasing the number of floors permitted in buildings (thus increasing FAR) in some areas (see Table 2.4 and Fig. 2.17). The plan also includes a vision related to outdoor thermal comfort: the “establishment of tree-lined boulevards and malls for comfortable walking and visual comfort”.

The tendency towards high-rise, high-density settlements is illustrated by a recent programme to relocate slum and shanty town residents to high-rise apartment buildings. The programme, called Compact Townships, is financed by selling prime land occupied by illegal settlements. However, of six relocation projects planned, only one has been implemented (Fig. 2.16).

The recent increasing number of high-rise buildings has been criticised, both for leading to abrupt social changes and for destroying the character of Colombo as a low-rise garden city (see e.g. Wijewardena 2005).

Fig. 2.16 (a) Illegal shanty town (above) and slum tenements (below). (b) High-rise residential building for relocated slum and shanty town residents (the Sahaspura project).

Urban design regulations

Sri Lanka is divided into provinces, each of which is subdivided into districts. In turn, the districts are divided into municipal and urban councils, as well as Pradeshiya Sabhas (van Horen 2002). The municipal councils govern larger urban areas (with a population typically above 30,000 inhabitants) whereas urban councils have smaller populations. Pradeshiya Sabhas are administrative units in smaller towns in predominantly rural areas. Colombo is situated in the Western Province, also called the Colombo Metropolitan Region, which comprises three districts (Fig. 2.14a).

In Sri Lanka, urban planning is governed by the Urban Development Authority (UDA). This authority is responsible for every urban area in the country which it has declared as being under its jurisdiction (van Horen 2002). The UDA elaborates both comprehensive and detailed urban plans.

In Colombo, the City of Colombo Development Plan (UDA 1999a, b) deals with urban regulations within the Colombo Municipal Council (Fig. 2.14b). Volume I of this document (UDA 1999a) deals with land-use zoning whereas Volume II (UDA 1999b) contains rules related to construction including specific rules regarding urban form. Additionally, some especially important areas within the city of Colombo will be covered by so-called development guide plans which give detailed guidance on environmental characteristics, urban form and architectural design. Outside the borders of the municipal council, the Housing and Town Improvement Ordinance (Gov. of Sri Lanka 1980) stipulates construction-related regulations including specific rules regarding urban form.

Land-use zones

The land-use zones that apply to the city of Colombo are described in Table 2.4 and shown in Fig. 2.17. The current land-use zones suggest considerably higher densities than those existing today. This particularly concerns the Concentrated development zone, where buildings should be *at least* ten storeys high and the Primary residential zone, where building heights up to ten storeys are permitted. The former include Fort and Pettah as well as the area just south of Fort. The latter is found along the coast south of Fort. The Special primary residential zone is found in Cinnamon Gardens, a traditional high income area.

Table 2.4 The land-use zones in Colombo (UDA 1999a)

Zone	*Land use*	*Description*
1	Special primary residential	Mainly residential, max. three storeys
2	Primary residential	Max. ten storeys
3	Commercial	Non-polluting, light industries
4	Mixed development	Mix of residential and commercial
5	Concentrated development	High density zone, min. ten storeys
6	Port-related activity	
7	Recreational	Recreation and residential
8	Environmental conservation	Preserved nature, limited recreation

Regulation of urban form

Current regulations governing the number of storeys, building height, distances between buildings, plot coverage, floor area ratio (FAR)[17] and setbacks are shown in Table 2.5. (Plot coverage, FAR, plot frontage and setbacks are illustrated in Fig. 2.10.)

17 FAR is calculated as the total floor area of a building, divided by the total area of the plot.

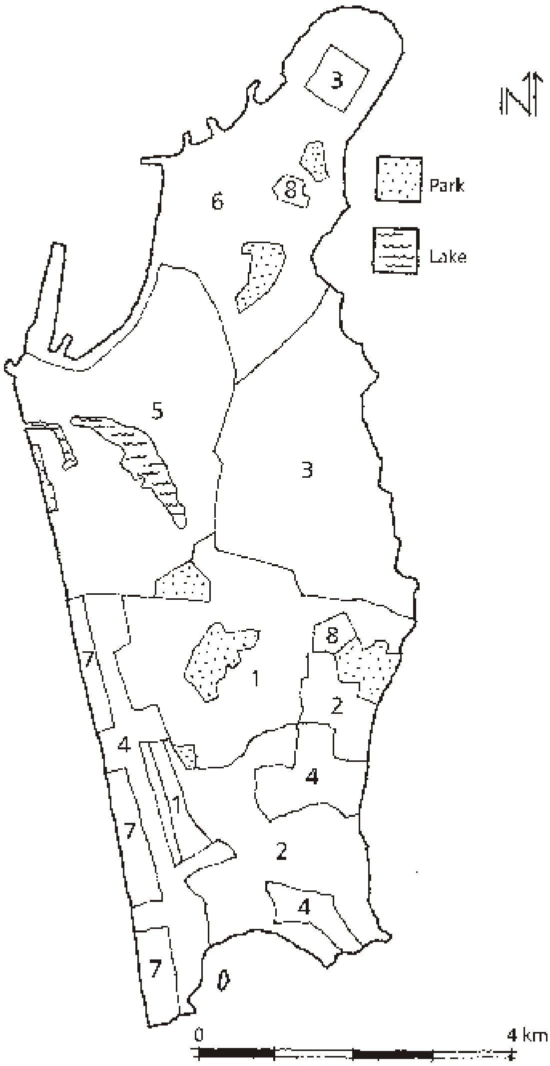


Fig. 2.17
The land-use zones for the Colombo Municipal Council as proposed by the UDA (1999a).
(The numbers refer to the land-use zones in Table 2.4)

As can be seen in Table 2.5, the maximum FAR is 1.5 for the smallest low-rise buildings and increases up to 8 for middle-rise buildings (and even higher for high-rise buildings). The maximum plot coverage is almost independent of plot size and building type. For buildings up to eight storeys, it is 65% for residential buildings and as high as 80% for non-residential purposes. For these categories, there are setback rules for the front and the rear of the buildings, but not for the sides. However, buildings higher than eight storeys are subject to setback requirements on all four sides. The minimum street width and setbacks increase with the height of the buildings. Up to six storeys, the front setback is only 1 m. However, this distance may be greater if a street line indicates possible future widening of the street.

Roof overhangs or any type of shading devices on the façade of a building are permitted to project up to 1.0 m beyond the building line. Footways under projecting verandas or the like, along the front

Table 2.5 The regulations pertaining to urban form in the city of Colombo. FAR = floor area ratio, H = building height.

Class of building	Type of use	Plot size (m^2)	Min. plot frontage (m)	Max. FAR	Max. plot coverage (%)	Max. no. of floors	Max. H (m)	Min. road width (m)	Minimum setbacks front (m)	rear (m)	side (m)
Low rise A	Residential	150–249	6	1.50	65	2	7.5	3	1[a]	2.3	—
	Non-residential			1.50	80						
Low rise B	Residential	150–249	6	2.00	65	3	11.25	6	1[a]	3.0	—
	Non-residential			2.25	80						
Intermediate rise A	Residential	250–399	8	3.00	65	5	18.75	6	1[a]	3.5	—
	Non-residential			3.75	80						
Intermediate rise B	Residential	400–749	10	3.75	65	6	22.5	9	1[a]	4.5	—
	Non-residential			4.50	80						
Intermediate rise C	Residential	750–999	15	5.00	65	8	30	9	2	5.0	—
	Non-residential			6.00	80						
Middle rise	Residential	1000–1999	30	7.50	65	12	45	12	3	6.5	6.5
	Non-residential			8.00	70						
High rise		≥ 2000	40	—[b]	50	≥ 13	≥ 46	12	3	10.0	10.0

a If there are no building lines.
b To be issued by the authority.

of the building, are only permitted if they are located within the building lot.

The building types shown in Table 2.5 do not include the buildings found in the historic core of the central Fort area. According to the proposed development guide plan for Fort (UDA 1999a), new or renovated buildings should be of the same type as existing ones, entailing, for example, that setbacks are not stipulated, although colonnades must be provided along all vehicular and pedestrian roads.

Areas studied

In this study, urban microclimate and outdoor thermal comfort was studied in detail in three neighbourhoods within the Colombo Municipal Council (zones 4 and 5) and in two neighbourhoods outside the municipal council. The position of the measurement sites are shown in Fig. 5.1. An analysis of the consequences of the urban regulations on outdoor thermal comfort is given in Section 6.4.

3 Concepts

This chapter describes the state-of-the-art regarding two concepts central to this study. The first section considers the influence of the built environment on the microclimate within the urban canopy layer. The second section deals with outdoor thermal comfort, including both theoretically derived comfort indices and aspects of climatic adaptation. *A glossary of terms and definitions is given in Appendix 1.*

3.1 The climate of the urban canopy layer

Urban climate on different scales

When countryside air flows over a city, different horizontal layers of air are formed, each of which develops its own climate (Fig. 3.1). According to Oke (2004), three climate scales apply in urban areas: the micro, local and meso scales (Fig. 3.1). The horizontal and vertical extensions of these scales are shown in Table 3.1. The micro-scale includes buildings, streets, squares, gardens, trees, etc. The local scale represents urban neighbourhoods, whereas the meso-scale represents an entire city.

Table 3.1 Horizontal and vertical scales of urban atmosphere (after Oke 2004).

Scale	*Urban level*	*Horizontal distance*	*Vertical layer*
Micro	Street canyons, squares, gardens	< 200–300 m	Roughness sub-layer
Local	Neighbourhood	100 m – 10 km	Inertial sub-layer
Meso	City	> 10 km	Mixing layer

Vertically, the micro-scale falls within the roughness sub-layer, the height of which depends on building density and atmospheric stability (Roth 2000). It has been found to vary between about 1.5 and 4 times the average height of the buildings (Oke 2004). Above this height, micro-climate effects from the buildings and objects below are phased out. The area between the ground and the rooftops is called the *urban canopy layer*. This layer, which constitutes the lower part of the roughness sub-layer, comprises buildings and the areas around them, such as gardens, streets, squares and parks.

This thesis focuses on the climate in the urban canopy layer (UCL), that is, the climate between the buildings (Fig. 3.1c). Within this layer, the microclimate is site-specific and varies greatly within short distances (Arnfield 2003, Oke 2004).

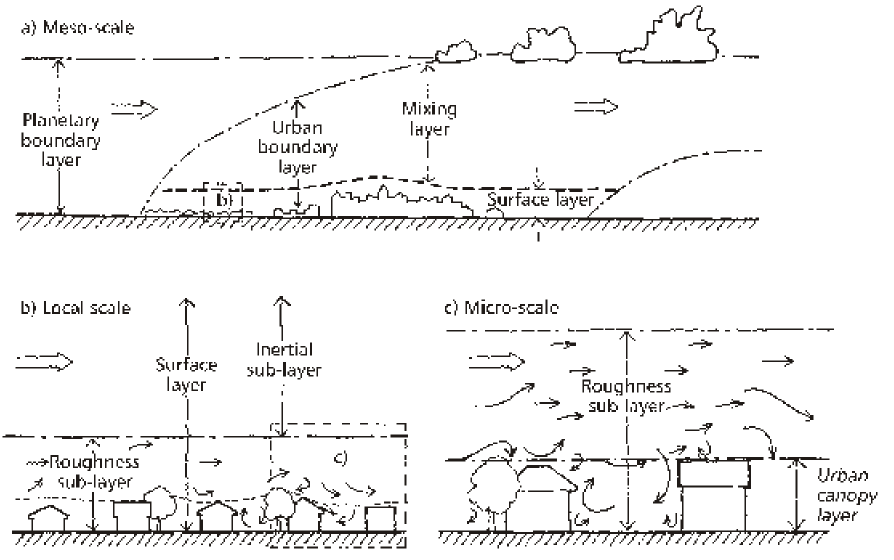


Fig. 3.1 Climatic scales in urban areas: meso, local and micro-scale (modified from Oke 2004).

Features of the built environment

Built-up areas influence the absorption and reflection of solar radiation, the ability to store heat, the absorption and emittance of long-wave radiation, winds and evapotranspiration. The built environment is also characterised by human activities affecting the climate, such as the heating and cooling of buildings, motor traffic and industrial production. These activities release heat and moisture but also pollute the air, which affects incoming and outgoing radiation.

Urban geometry and properties of surface materials

It is generally agreed that the geometric form of the urban canopy layer greatly influences the urban climate (Arnfield 2003). A common element within the canopy layer, particularly in city centres, is a street flanked on both sides by rows of buildings. This simplified element of the urban environment, referred to as the urban street canyon (Fig. 3.3), is determined geometrically by the ratio between the height of the façades and the width of the street (H/W ratio). For asymmetric canyons with varying building heights, the H/W ratio is calculated using the average building height.

The thermal properties of surface materials also greatly influence the urban climate (Arnfield 2003). The reflectivity, or albedo, of surfaces, determining the amount of absorbed short-wave radiation, depends mainly on the colour of the surface and varies greatly in urban areas: between about 0.3 for light colours up to about 0.9 for dark colours. Conversely, the ability to emit and absorb heat (long-wave radiation) is very similar for rural and urban surface materials whose emissivities lie around 0.9 (one exception being shiny metallic surfaces, which have considerably lower values).

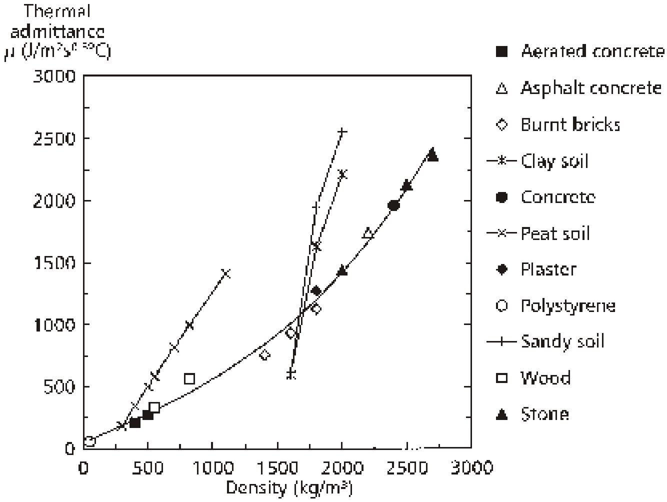
Thermal admittance μ is identified by Oke (1987) as the key parameter in determining how much of the radiation absorbed at the surface will be stored in the sub-surface; the higher the thermal admittance, the more heat will be stored in the material while less energy will be released as sensible heat. Thermal admittance, sometimes called the heat penetration coefficient (McIntyre 1980), is calculated as:

$$\mu = \sqrt{\lambda \ C} \qquad (3.1)$$

where λ represents thermal conductivity and C the thermal capacity of the material. Fig. 3.2 shows how thermal admittance increases with the density of building materials and moisture content of soils.

Fig. 3.2
The relation between thermal admittance μ and density of building materials and soils. For soils, lower values are for dry soils and the higher values for saturated conditions.

Sources: Evans (1980), Oke (1987) and Szokolay (2002).



In Fig. 3.2, it can be seen that dry soils have lower thermal admittance than typical urban surfaces, such as concrete, asphalt and stone. However, the values for moist soils are similar to, or even higher than, those of urban materials. However, due to the irregular urban geometry, the active surface, i.e. the surface exposed to the air, is considerably larger in urban areas than in rural areas (Oke et al. 1999).

Thermal and surface properties for some common urban and rural materials are shown in Appendix 2.

Anthropogenic heat

To a greater or lesser extent, all cities release heat from space heating, air conditioning, motor traffic and other domestic and industrial activities that require energy. According to Oke (1982), typical values for anthropogenic heat in temperate climates vary between 5 W/m^2 in residential suburbs and 50 W/m^2 in the centres of large cities. These values are low compared to the radiation energy flux in urban areas (Fig. 3.6).

Air pollution

Air pollution from motor vehicles and industrial activities adds to the aerosols in the air. Consequently, incoming solar radiation is attenuated and its diffuse component increased. For most cities, the reduction of global solar radiation is normally below 10%, but may exceed 20% in highly polluted cities (Oke 1988b, Arnfield 2003). Another effect of pollution is that a larger part of the outgoing long-wave radiation will be absorbed by the atmosphere and re-emitted towards the ground (Oke 1987).

Green areas and vegetation

In urban areas, bare and vegetated soils are largely replaced by hard, often waterproof, surfaces. Consequently, much of the ground's ability to release energy through evaporation and transpiration is lost. However, green areas within cities act similarly to rural areas and are normally cooler than built-up areas, especially by night. Irrigated green areas can be considerably cooler than their surroundings, even during daytime, especially in semi-arid and arid areas.

Single trees and small clusters of trees can be effective in providing shade. The shading of solar radiation – including direct, diffuse and reflected radiation (from the walls and the street) – will keep urban surfaces cooler, in turn, decreasing air temperature.

Influence of the built environment on urban climate

Short and long-wave radiation

The amount of absorbed solar radiation in an urban area depends both on the reflectivities of the urban surfaces and on the canyon geometry. The absorbed short-wave radiation K^* at a single surface is calculated as (Oke 1987):

$$K^* = K\downarrow - K\uparrow = (S + D) - \alpha(S + D) = (1 - \alpha)(S + D) \qquad (3.2)$$

where $K\downarrow$ is the incoming global radiation, $K\uparrow$ is the reflected radiation, S and D are the direct-beam and diffuse radiation components, respectively, and α is the reflectivity of short-wave radiation.

The direct-beam irradiation S on a surface depends on its orientation and on the azimuth and altitude angles of the sun. The amount of diffuse irradiation D received at street level depends on the sky view factor (SVF), which expresses the portion of the sky seen from the street as illustrated in Fig. 3.3. D decreases with decreasing sky view factor.

Whereas there is often little difference in reflectivity between urban and rural surfaces (Appendix 2), the *overall reflectivity* of the urban fabric is generally lower than for rural surfaces. This is because the irregular urban surface tends to trap solar radiation. Due to multiple reflections within the canyons, the amount reflected back to the

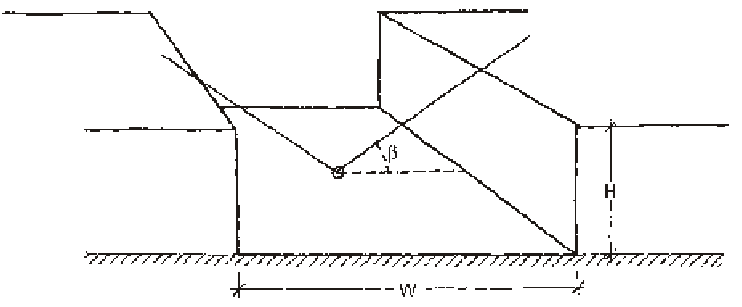


Fig. 3.3 Sky view factor of an urban street canyon. At the middle of the street of an infinitely long canyon, SVF = cosβ.

atmosphere is small. Steemers et al. (1998) studied the reflectivity of the entire urban fabrics of some European cities, both through scale modelling and simulations using the tool Radiance, and found that, compared to a flat surface of the same colour, the decrease in reflectivity of urban fabrics can be as great as 40%. Using numerical simulations with a model that takes multiple reflections into account, Arnfield (1990a) could show that the overall reflectivity of global solar radiation ($S + D$) for an urban canyon typically varies between 0.06 and 0.15 (Arnfield 1990a). Reflectivity decreases approaching the equator and with an increasing H/W ratio.

The net long-wave radiation L^* at an urban surface is calculated as (Oke 1987):

$$L^* = L\downarrow - L\uparrow \tag{3.3}$$

where $L\downarrow$ is the incoming long-wave radiation from the sky and $L\uparrow$ is the emitted long-wave radiation from the surface. The outgoing long-wave radiation $L\uparrow$ is always greater than the atmospheric counter-radiation $L\downarrow$ and therefore L^* is negative.

The magnitude of the incoming long-wave radiation from the sky $L\downarrow$ depends on the air temperature and atmospheric emissivity. The latter depends, in turn, on the humidity, the cloud cover and the type of clouds (Arnfield 1990b, Oke et al. 1991). $L\downarrow$ is fairly constant throughout the day and typically varies between about 300 W/m^2 for clear skies to about 400 W/m^2 for skies with high humidity and cloud cover (Oke et al. 1991, Jonsson et al. 2005). As with diffuse radiation, the amount of incoming long-wave radiation from the sky reaching street level decreases with decreasing SVF.

The outgoing radiation from an urban canyon is complex. Apart from radiative exchange with the sky, the canyon surfaces will also exchange radiation with each other. For a single surface, the emitted long-wave radiation can be expressed as (Oke 1987):

$$L\uparrow = \varepsilon \sigma T_s^4 \tag{3.4}$$

where ε is the emissivity for long-wave radiation at the surface (see Appendix 2), σ is the Stefan-Boltzmann constant = 5.67 10^{-8} W/m^{2}K^4 and T_s is the temperature of the surface (in degrees Kelvin). Similarly to incoming long-wave radiation, the outgoing long-wave radiation from a canyon is linked to the SVF; the lower the SVF, the lower the $L\uparrow$ from the canyon. Consequently L^* diminishes with lower SVF (higher H/W ratio).

Air temperature

The best known characteristic of the urban climate is that cities are warmer than their rural surroundings. The urban *heat island*, which is primarily a nocturnal phenomenon, has been studied extensively throughout the 20th century (see e.g. Landsberg 1981, Oke 1982, Arnfield 2003). During the daytime, urban-rural temperature differences are normally smaller and, as a consequence of the nocturnal heat island, the diurnal temperature range is less in urban areas than in rural areas.

Field studies in numerous cities, mainly in temperate climates, have shown that the magnitude of nocturnal heat islands increases with increasing H/W ratio (reduced SVF) of street canyons (see e.g. Oke 1982). The link between the nocturnal heat island and canyon geometry has been confirmed by Arnfield (1990b) and Oke et al. (1991) through the simulation of canyon surface temperatures. These studies also demonstrated that the size of the heat island increases with increasing urban-rural differences in thermal admittance. By day, the urban canyon is a good absorber of solar energy and, because of the relatively high thermal capacity of urban surface materials, this energy is stored in the fabric and not released until after sunset (Nakamura and Oke 1988). The size of the urban heat island decreases with increasing emissivity from the sky (e.g. due to increased cloud cover) and with increased wind speed (Oke 1982). Consequently, the largest urban-rural temperature differences occur during calm and cloudless nights.

By day, both heat and *cool* islands can be found. Daytime heat islands are normally believed to be caused by anthropogenic heat, whereas cool islands are attributed to the shade cast by buildings (Oke 1982).

An extensive study of summertime air temperature distribution in an urban canyon with H/W ≈ 1 in Kyoto (35°N), Japan, revealed that the air temperature within the canyon was uniform except for within about 1m from the canyon's surfaces (Nakamura and Oke 1988). This is because the air mixes well due to natural and forced convection.

The impact of anthropogenic heat on air temperature is often small and seldom a major cause of urban warming, except in some cities where extensive space heating or cooling is common and buildings are poorly insulated (Oke et al. 1991, Arnfield 2003).

Air pollution reduces both net incoming short-wave radiation K^* and net outgoing long-wave radiation L^* and consequently the net effect on the radiation budget ($K^* + L^*$) is small. This explains why air pollution has a surprisingly limited effect on air temperature (Oke 1987, Arnfield 2003).

Green areas and vegetation can have a significant impact on air temperature. Larger parks are cooler than built-up areas. Temperature differences of 1–2°C are common (Oke 1989) but can reach as much as 5°C (Spronken-Smith and Oke 1998, Upmanis et al. 1998). The major reasons for parks being cooler by night include more efficient cooling of the ground through net outgoing long-wave radiation due to higher SVF and less heat storage in surfaces compared to street canyons.

In arid regions, irrigated green areas may be considerably cooler than built-up areas due to the so-called oasis effect (Oke 1987). If there is an excess of water, evaporation from vegetation and moist soil becomes so strong that energy is taken from the air, causing it to cool. However, if irrigation ceases, the effect will eventually disappear.

For single trees and small clusters of trees, the effect of evaporation on air temperature is marginal; Oke (1989) estimates this to be lower than 0.5°C. However, due to shading of the ground, air temperatures may be reduced. Shashua-Bar and Hoffman (2000) found 2–4°C cooler air temperatures in tree-lined streets in Tel Aviv, Israel.

They also found that during the night, the trees blocked the outgoing long-wave radiation from the canyon surfaces and nocturnal cooling was therefore reduced. Consequently, the trees helped create a more conservative climate with cooler days and warmer nights.

Humidity

In general, urban-rural humidity differences are small. However, there is a tendency for cities to be slightly more humid by night and dryer by day than their rural surroundings (Oke 1987). This phenomenon is often called urban moisture excess (Holmer and Eliasson 1999, Mayer et al. 2003). The fact that cities are, in general, more humid by night is believed to enhance the heat island effect slightly, since the incoming long-wave radiation $L\downarrow$ above cities increases compared to the surrounding rural areas (Oke et al. 1991).

Wind

The complex geometrical forms of urban areas, comprising buildings with sharp edges, strongly affect regional winds blowing through and over a city. Measurements and wind tunnel tests have shown that regional horizontal wind speed is reduced to 25–50% (Glaumann and Westerberg 1988, Bosselmann et al. 1995). However, the wind pattern is highly irregular and characterised by a high level of gustiness. Locally, wind speeds in urban areas can exceed those of the rural surroundings, especially in the presence of high-rise buildings (Oke 1987, Bosselmann et al. 1995).

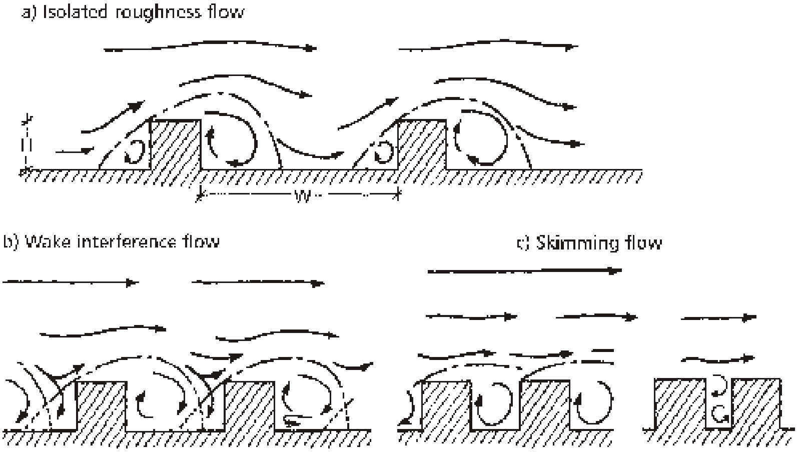


Fig. 3.4 Air flow in street canyons with different H/W ratios (Modified after Oke 1987 and Santamouris 2001). The closer the buildings, the more the air flow tends to skim over them.

Because of the variation in the size and shape of buildings and the distances between them, air movements in urban areas become extremely complex and it is very difficult to calculate or estimate properties such as direction, speed and gustiness. However, using wind tunnel tests and field measurements, some basic wind phenomena have been observed and are summarised by Oke (1987, 1988a). For several parallel and symmetrical urban canyons, the wind flow perpendicular to the long-axis of the canyon will depend on the H/W ratio according to Fig. 3.4. For H/W < 0.3, a low pressure zone is formed behind the buildings on the leeward side with a circulatory vortex flow. At these low H/W ratios, most of the wind flow enters the canyon. As distances between the rows of buildings decrease, the vortex flow will be reinforced because of downward deflection by the next building. For H/W > 0.65, a stable circulatory vortex develops within the canyon and the coupling with the air above the canyon becomes weaker, causing most of the flow to skim over the buildings. In deep canyons, a secondary vortex is common, located beneath the first and rotating in the opposite direction (Fig. 3.4c). The coupling between the canyon and the air above it thereby decreases with increasing H/W ratio. In deep canyons, this results in the canyon air becoming isolated from the air above.

The wind patterns may be more complex for irregular urban forms and for wind directions other than perpendicular. For wind flows parallel to an urban canyon, wind speeds may be increased due to channelling (Oke 1987).

The energy balance of an urban canyon

In recent decades, urban climate research has, to a great extent, focused on the energy balance of urban areas (Arnfield 2003). This balance includes all the energy processes involved in the formation of the urban climate and illustrates the diurnal variation of different energy fluxes and how they relate to each other. The basic idea is that the input from radiation and anthropogenic heat has to be balanced with the release of sensible and latent heat. However, there is also heat entering and leaving the canyon through the horizontal transport of air (advection) and heat that is stored in the urban surfaces.

For a volume consisting of a street canyon (Fig. 3.5), or a larger urban area, the energy balance is normally expressed as (Oke 1987, Arnfield 2003):

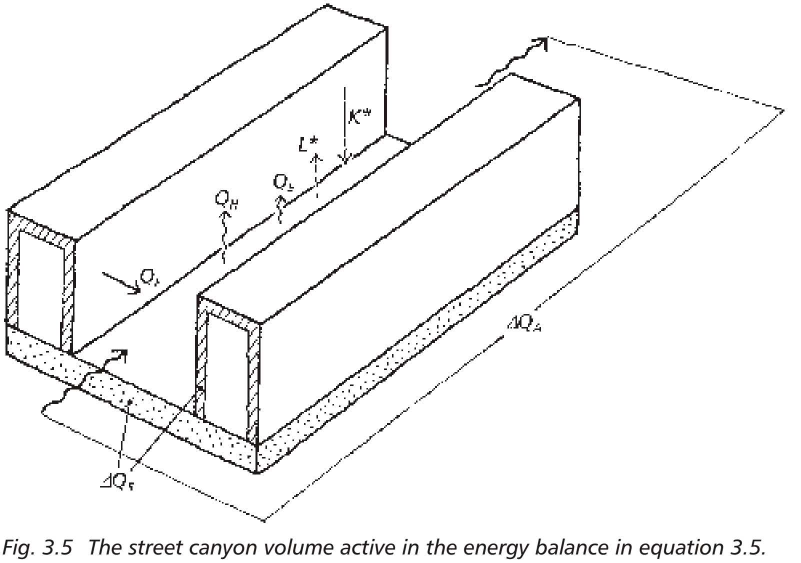


Fig. 3.5 The street canyon volume active in the energy balance in equation 3.5. The boundaries of the volume consist of the canyon top, the inner surface of the canyon walls and the lower limit of the active soil.

$$(K^* + L^*) + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A \qquad (3.5)$$

where K^* and L^* are net incoming short and long-wave radiation respectively, Q_F is anthropogenic heat, Q_H is sensible heat, Q_E is latent heat, ΔQ_S represents net heat storage and ΔQ_A is the net advection through the sides of the volume. All fluxes are in W/m^2.

The net radiation[1], K^*+L^*, is positive during the day because the absorbed solar radiation is greater than the net outgoing long-wave radiation (Fig. 3.6). At night, however, when there is no solar radiation ($K^* = 0$), net radiation consists entirely of net outgoing long-wave radiation (L^*) and is therefore negative. As mentioned above, anthropogenic heat Q_F is normally small compared to the radiation input.

The sensible heat Q_H released (or absorbed) depends on the turbulence of the atmosphere and the temperature gradient between the surface and the air. The Q_H released from a surface can be calculated as (Arnfield and Grimmond 1998):

$$Q_H = h(T_s - T_a) \qquad (3.6)$$

where h is the overall heat transfer coefficient from radiation and convection, T_s is the surface temperature and T_a is the air temperature. From equation 3.6, it can be seen that Q_H increases with increased convection and increased air-surface temperature difference. Consequently, Q_H is high during the day when both surface temperature and natural convection are high, particularly on sunny days (Fig. 3.6).

Similarly to Q_H, latent heat Q_E is dependent on air turbulence (the more turbulent, the higher Q_E) and the humidity gradient (the greater the difference in humidity between the surface and the air, the higher the Q_E). Consequently, Q_E will be great when surfaces are moist and when the surrounding air is dry. If the release of latent heat Q_E increases due to evaporation, the sensible heat Q_H will diminish (at extreme evaporation rates, Q_H may become negative and the air cools, causing the "oasis effect" mentioned above).

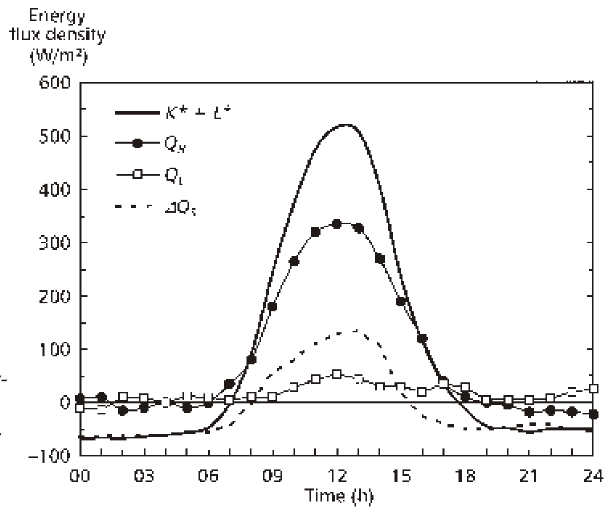


Fig. 3.6
The energy balance according to equation 3.5 for an urban canyon in Vancouver, Canada. K^*+L^* = net short and long-wave radiation, Q_H = sensible heat, Q_E = latent heat and ΔQ_S = heat storage. The anthropogenic heat Q_F and advection ΔQ_A were not measured and are included in the other heat fluxes. They are, however, assumed to be small. (Modified after Oke 1987).

1 The all-wave net radiation K^*+L^* is often denoted Q^*.

The heat storage component ΔQ_S comprises heat stored in urban surfaces, both in façades and in the ground down to the depth at which each surface is active. Its magnitude depends on the heat capacity and thermal admittance of the canyon surfaces (see Appendix 2). As can be seen in Fig. 3.6, ΔQ_S is mainly positive during the day (heat is stored in the urban surfaces) and negative during the night (heat is released from urban surfaces).

The advective component ΔQ_A, which consists of horizontal air movements between urban and rural sites, or between different urban sites, depends on the wind speed and how permeable the urban area is to air movements. However, for urban sites surrounded by areas of similar urban form and land use, ΔQ_A can often be neglected, assuming no net horizontal energy exchange, especially if wind speeds are low (Oke 1987, Oke 1988b).

In Fig. 3.6, it can be seen that net daytime radiation (K^*+L^*) results primarily in sensible heat Q_H and heat storage ΔQ_S. The canyon in question had a gravelled road, resulting in a small amount of latent heat Q_E (for impervious surfaces, Q_E is normally negligible). Moreover, it can be seen that during the night, the net outgoing long-wave radiation L^* (negative) equals the release of heat from the surfaces (ΔQ_S is also negative).

In this study, the energy balance of the urban canyon (equation 3.5) was used to identify strategies to improve the microclimate, see Section 5.2 and Paper IV.

3.2 Outdoor thermal comfort

According to ASHRAE, thermal comfort is defined as the "condition of mind that expresses satisfaction with the thermal environment" (ASHRAE 1997). Another definition is the absence of thermal discomfort, that is to say, that an individual feels neither too warm nor too cold (McIntyre 1980). The temperature of this state is referred to as the *neutral temperature*. However, thermal sensation is subjective, meaning that not all people will experience comfort in the same thermal environment. For indoor conditions, comfort zones are typically implemented to satisfy 80% of people (Fountain and Huizenga 1994). The comfort zone is often expressed as a temperature range around the neutral temperature.

Outdoors, the thermal comfort range is wider than indoors, spanning from thermal comfort to a stressful environment (Spagnolo and de Dear 2003, Emmanuel 2005a). Moreover, outdoor conditions show large temporal and spatial variations and the thermal balance of the body is seldom in steady state as it is in controlled indoor environments. In warm climates, which are the focus of this study, it is well known that mental and physical performance deteriorates at high temperatures and that heat stress may lead to heat-related illness (McIntyre 1980).

The heat balance of the human body

A good way to illustrate all of the variables that influence thermal comfort, and how these inter-relate, is to study the energy balance of the human body. Many of the most common thermal indices for indoor conditions are based on this heat balance (McIntyre 1980).

The input in the heat balance is the metabolic heat production of the body and the output is the sum of heat losses through *sensible heat flow* from the skin, *evaporation* from the skin and *respiration*. The heat balance can be expressed as (see e.g. McIntyre 1980, ASHRAE 1997, Höppe 1999):

$$M = (R + C) + (E_{dif} + E_{sw}) + (C_{res} + E_{res}) \tag{3.7}$$

where M is the internal heat production of the human body, R and C are the radiation and convection heat losses from the outer surface of the clothed body (or exposed skin) respectively, E_{dif} is heat loss by evaporation of moisture diffused through the skin, E_{sw} is heat loss through the evaporation of sweat and C_{res} and E_{res} are the convective and evaporative heat losses through respiration respectively.

From a thermo-regulatory perspective, equation 3.7 represents the requirement for thermal comfort, i.e. heat production must equal heat losses (McIntyre 1980, Höppe 2002). If the body is not in thermal balance its temperature will change and eventually become uncomfortable. However, the heat balance can be maintained by physiological mechanisms, e.g. sweating, even if the body is not thermally comfortable. Therefore, an additional requirement for the state of thermal comfort is that mean skin temperature and the rate of sweating should maintain appropriate levels (McIntyre 1980, Höppe 2002).

In this study, the energy balance of the human body (equation 3.7) was used to identify strategies to improve the microclimate, see Section 5.2 and Paper IV.

Variables influencing thermal comfort

There are four environmental variables affecting the thermal comfort of the human body: air temperature, mean radiant temperature, air humidity and air speed. Additionally, two personal variables influence thermal comfort: clothing and the level of activity. However, other personal factors related to adaptation and acclimatisation have proven to affect thermal sensation and are discussed below.

Air temperature

The air temperature, defined as the dry-bulb temperature in the shade, is one of the most important climatic factors influencing thermal comfort. Both the body's convective heat loss C and its dry respiration heat loss C_{res} decrease with increasing air temperature. If the air temperature exceeds the surface temperature of the clothed body, or of the exposed skin, which is around 34°C, C is negative and there will be convective heat gain.

Radiation

The absorption of solar radiation and the exchange of long-wave radiation strongly affect the state of thermal comfort of the human body. For indoor conditions, the concept of mean radiant temperature (MRT) was developed. This is defined as "the uniform temperature of an imaginary enclosure in which radiant heat transfer from the human body equals the radiant heat transfer in the actual non-

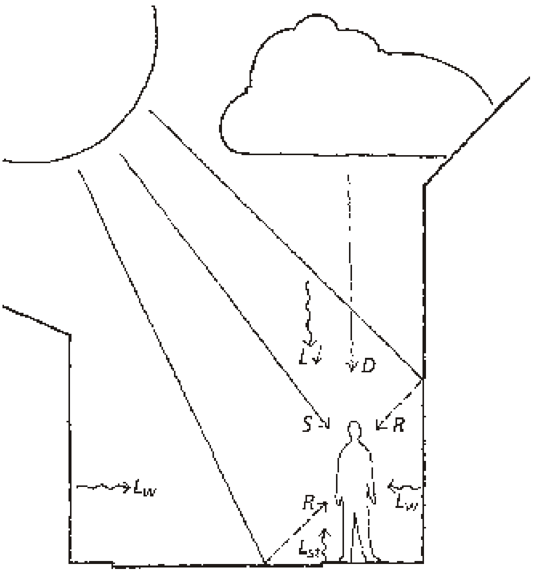


Fig. 3.7
A person in a street canyon exposed to direct (S), diffuse (D) and reflected (R) short-wave radiation as well as long-wave radiation from the sky (L↓) and the urban surfaces (L_w and L_{st}).

uniform enclosure” (ASHRAE 1997). Indoors, where short-wave radiation is normally absent, the body exchanges long-wave radiation with the six room surfaces and the MRT can be calculated by weighting the influence of the temperatures of each surface (see e.g. McIntyre 1980, ASHRAE 1997). Outdoors it is much more complicated to determine MRT because of the extensive variation in radiation from different sources (Fig. 3.7). The human body may receive solar radiation as direct and diffuse, as well as reflected radiation from building façades and the ground. Moreover, the body exchanges long-wave radiation with the sky, with urban surfaces and with objects such as trees. The magnitude of the radiation from the different sources varies greatly in space and time. The most accurate way to determine outdoor MRT is by measuring the short and long-wave radiation from different directions and then calculating MRT (see e.g. VDI 1998, Spagnolo and de Dear 2003, Ali-Toudert et al. 2005). However, MRT can also be measured using a globe thermometer (see e.g. Nikolopoulou et al. 2001) or can be estimated through calculations (Matzarakis 2000, Ali-Toudert and Mayer 2006).

The radiant heat loss R of the human body decreases with increasing MRT. When MRT is higher than the temperature of the outer surface of the clothed body (or exposed skin), there is a radiative heat gain. Otherwise, R is positive and there is a radiative heat loss.

Air humidity

A change in the humidity of the atmosphere affects thermal sensation in that a person feels warmer, sweatier and less comfortable (McIntyre 1980). Especially under warm conditions, when both convective C and radiative R heat losses are small, sweat evaporation E_{sw} is an important mechanism in maintaining comfort. When the liquid sweat on the skin surface evaporates, latent heat is extracted from the body and a cooling effect is produced.

The humidity of the air influences both evaporative (E_{dif} and E_{sw}) and respiratory (E_{res}) heat losses. As humidity increases, evaporative losses will decrease. However, according to Givoni (1998) humidity does not influence thermal sensation below a critical level. This is because, although the evaporative capacity of the air diminishes with increasing humidity, the body compensates for this by spreading the sweat over a larger area of skin, thus maintaining the required evaporation rate. The same author claims, however, that above a certain critical level of humidity, part of the latent heat of vaporisation is taken from the ambient air instead of from the skin. This will lead to more sweat production and thus increased discomfort due to the feeling of excessive skin wetness[2]. For subjects with sedentary activity, Givoni (1998) has defined this limit to 80% relative humidity for temperatures up to 25°C, corresponding to a vapour pressure of about 25 hPa.

Air speed

Air speed is a major factor affecting the state of thermal comfort. Outdoors, winds change speed and direction rapidly and a high degree of turbulence makes the wind speed feel higher than the measured mean value (Glaumann and Westerberg 1988, Bosselmann et al. 1995).

Both the convective heat loss C and the evaporation of sweat E_{sw} increase with increasing air speed because both the convective and evaporative heat transfer coefficients increase in magnitude (the insulating boundary layer around the body becomes smaller). Strong air movement is thus a disadvantage in cold climates, but a clear advantage in hot climates.

Personal factors

Metabolic heat M depends on the level of activity, which tends to vary more outdoors than indoors, typically from sitting to fast walking. Outdoors, people dress according to seasonal climate variations. Increased clothing insulation leads to a lower temperature difference between the outer surface of the clothed body and the ambient air temperature. Consequently, the convective C and radiative R heat losses decrease with increasing clothing insulation.

People adapt physically to an environment by adjusting how they dress and move, e.g. slow walking in hot climates, and by avoiding exposure to extreme climate situations etc. (Nikolopoulou and Steemers 2003).

Psychological factors also influence thermal comfort. These factors have gained more attention in recent years because discrepancies have been found between predictions using thermal indices and subjective thermal sensation. These discrepancies have been found both indoors and outdoors and give evidence to the fact that people adapt to their thermal environment (Brager and de Dear 1998, Emmanuel 2005a). However, psychological factors are likely to be greater outdoors where the environment is much more complex and dynamic (Nikolopoulou and Steemers 2003).

2 Skin wetness is the ratio between the actual and maximum evaporative loss at the skin surface. At maximum loss, the whole skin surface is wet.

In the hot humid climate of Bangkok (14°N), Thailand, Busch (1992) found that people spending most of their time in naturally ventilated (passive) buildings tended to accept higher indoor temperatures than those spending most of their time in air conditioned buildings. He attributed the results to this difference in "background" experience: people accustomed to cool, air conditioned environments expected, and preferred, it to be colder, whereas people who spent most of their time in warm, non-air conditioned environments expected it to be warm. In the warm-temperate climate of Sydney (34°S), Australia, Spagnolo and de Dear (2003) found that the comfort zone was wider outdoors than indoors. Their explanation is that people's expectations are different outdoors because the thermal environment varies much more in time and space and there is no way people can control it.

Another factor that has proven to influence thermal sensation is thermal history, i.e. the climate a person has recently been exposed to (Spagnolo and de Dear 2003, Thorsson et al. 2004). E g, a person who has been exposed to extreme heat for a long time and moves to a shady location will experience a different thermal sensation than someone who has spent a long period of time in the shady environment.

Thermal comfort indices

A thermal comfort index combines two or more variables into one single index. A great number of indices trying to predict the state of thermal comfort, mainly for indoor applications but also for the outdoors, have been developed (McIntyre 1980, Emmanuel 2005a).

Special outdoor thermal indices

Some thermal comfort indices have been specially developed for the outdoors. Some indices, such as the Index of Thermal Stress (ITS) (McIntyre 1980, Givoni 1998) and the Wet-Bulb Globe Temperature index (WBGT) (McIntyre 1980, Emmanuel 1997 and 2005a), have mainly been developed for extremely warm outdoor conditions, such as hot work places and military activities. Consequently, they can be classified as heat stress indices rather than comfort indices (McIntyre 1980). Another index widely used in outdoor applications is the temperature-humidity index (THI), which combines air temperature and relative humidity (McIntyre 1980, Bitan and Potchter 1995, Emmanuel 1997, Deosthali 2000, Emmanuel 2005b). However, this index has the disadvantage of considering neither radiation nor air speed.

There also exist empirically derived multivariable regression models, which calculate thermal sensation based on measured air temperature, solar radiation, humidity and wind speed (see e.g. Givoni et al. 2003, Nikolopoulou et al. 2003). Regression coefficients are derived from subjective comfort votes given by individuals. These models have proven to accurately predict thermal comfort but have the disadvantage of being restricted to the type of environment and climate in which the study took place.

Thermal comfort indices based on the heat balance

The most commonly used thermal comfort indices for indoor applications are based on the heat balance of the human body, e.g. the new effective temperature (ET*), the standard effective temperature (SET*), the predicted mean vote (PMV) and the physiologically equivalent temperature (PET). These indices have in common that they take into account all environmental variables influencing thermal comfort.

Both ET* and SET*, which are expressed in °C, are calculated with the same two-node model, where the heat balance between the environment and a cylinder is calculated in an iterative process until equilibrium is reached, normally after one hour (Fountain and Huizenga 1994). The difference between them is that SET* also incorporates the level of activity and clothing insulation. A special feature of ET* and SET* is that in cold environments, thermal comfort is related to skin temperature (which is a good predictor of thermal sensation) whereas in warm environments it is determined by the skin wetness. The reason is that skin temperature changes are small in warm environments where sweating occurs (Fountain and Huizenga 1994). ET* and SET* have been validated by extensive climate chamber studies establishing the comfort zones (Fountain and Huizenga 1994). Recently, Pickup and de Dear (2000) adapted SET* to outdoor conditions, calling the index OUT_SET*, by developing a model to calculate MRT in the complex outdoor environment.

PMV, which is the most widely used thermal comfort index, has proven to provide reliable results for thermal environments close to thermal comfort. Like SET*, the PMV index includes the level of activity and clothing insulation. A limitation with PMV is that the heat balance includes assumptions that are valid only for low to moderate levels of activity and light indoor clothing (Fountain and Huizenga 1994, de Dear and Pickup 2000). It does not, e.g., take the vapour resistance of clothing into account, which means that the index overestimates the ability of sweat to evaporate from the clothed body. Moreover, when humidity is high, PMV does not account for a reduction in sweating. The thermal sensation in hot humid environments will thus be worse than the PMV index predicts. PMV was recently extended to better predict indoor comfort in naturally ventilated buildings in warm climates by including an expectancy factor (Fanger and Toftum 2002).

PET, which is expressed in °C, is based on a combination of the heat balance model MEMI (Höppe 1993) and a parts of the two-node model used for ET* and SET* (Höppe 1999). It is defined as "the physiologically equivalent air temperature at any given place (outdoors or indoors) and is equivalent to the air temperature at which, in a typical indoor setting, the heat balance of a human body is maintained with core and skin temperatures equal to those under the conditions being assessed" (Höppe 1999). The conditions of the indoor reference climate entail air temperature equal to MRT, wind speed of 0.1 m/s ("still" air) and vapour pressure of 12 hPa. For a sedentary person wearing typical indoor clothing, thermal comfort is defined as PET values between 18 and 23°C (Matzarakis et al. 1999). PET differs from e.g. the PMV model in that it uses real values for skin temperature and sweat evaporation. The latter is a function of both mean skin temperature and the core temperature of the body (Mayer and Höppe 1987). Calculations of heat flux from the core to the skin and to the outer surface of the clothing are similar to ET* and SET* (VDI 1998).

There are several limitations with the thermal indices described above. A common feature is that they often fail to correctly predict the thermal sensation in environments outside the comfort zone or under dynamically changing conditions (Fountain and Huizenga 1994). According to Oseland and Humphreys (1994) one reason for this is that subjective thermal sensation can be quite different from the physiological state of the body, especially if climatic conditions are not steady or if there are abrupt changes in activity and clothing. Another problem is that none of the indices have been properly validated for the outdoors.

Although the applicability of the indices described above is limited, they have several advantages. For example, they take all environmental variables into account and consequently provide a comprehensive picture of the thermal environment. Moreover, they are universal, which makes it is possible to compare results from different thermal environments.

In this study, activity and clothing have not been considered, thus excluding the SET* and PMV indices. Instead PET was chosen. It was preferred to ET*, since it has been more commonly applied in outdoor environments.

4 Literature review

This chapter contains a literature review of topics central to this thesis. The first two sections deal with the urban microclimate and outdoor thermal comfort respectively. Contrary to the general overview in Chapter 3, the emphasis here is on cities in hot dry and hot humid climates. The third section presents models and tools to predict the urban microclimate and the fourth section treats urban design guidelines for tropical climates. Section five is a review of the consideration of climate aspects in urban planning and design.

4.1 Microclimate in tropical cities

Most studies in tropical cites have dealt with urban-rural differences, but there are also a few studies on intra-urban microclimate variation.

Urban-rural differences

Air temperature

Jonsson and Lindqvist (2005) reviewed 13 studies and conducted two in tropical, predominantly hot humid, climates. Nocturnal heat islands typically varied by between 2 and 5°C. In general, heat islands in the cities studied were of smaller magnitudes than those found in temperate climates. Moreover, almost all studies show that nocturnal urban heat islands are at their largest during the dry season. Jonsson and Lindqvist (2005) explain the smaller urban-rural temperature differences as being attributable to more humid rural surroundings and higher sky emissivity. There are few studies from hot dry cities, although the summertime nocturnal heat island in Phoenix (33°N), Arizona (USA), is around 6°C, which is similar to temperate climates (Baker et al. 2002). However, Nasrallah et al. (1990) found a heat island of only 2°C in the hot dry maritime climate of Kuwait City. They explain this low value as being attributable to the moderating effect of the Persian Gulf.

Daytime conditions have gained far less attention than nocturnal heat islands, although the former are more important from a human comfort point of view. In their comparison of tropical urban heat island studies, Jonsson and Linqvist (2005) report mainly daytime heat islands and very few cool islands. Jáuregui (1997) found fairly high daytime heat islands in the tropical highland city of Mexico City (19°N): 2.5°C in the wet season and 4–5°C in the dry season. He attributes the latter to the higher absorption of solar radiation by urban surfaces compared to surfaces in rural areas. Jonsson and Linqvist (2005) found small but frequent cool islands in Ouagadougo (12°N), Burkina Faso, especially during the wet season, and attribute these to evaporative cooling in the city (the rural station was dryer). They also found cool islands in Dar es Salaam (7°S), Tanzania, but these were smaller and less frequent and are believed to be a result of the sea breeze (the rural station was situated inland from the city).

Humidity

There are few studies on urban-rural humidity differences. In Mexico City, Jáuregui and Tejeda (1997) found that the specific humidity in urban areas reached its peak in the evening and remained high throughout the night. A few hours after sunrise, humidity began to fall, reaching its minimum in the afternoon. This tendency was also found by Adebayo (1991), although he studied only daytime variations. Conversely, Ali-Toudert et al. (2005) found that the vapour pressure in the hot dry desert city of Beni-Isguen (32°N), Algeria, was higher by day than by night. They suggest that a possible explanation for this may be the use of water in the kitchens, which are situated close to the streets.

Air temperature variations within urban areas

Field studies

A few authors have studied the effect of urban geometry on daytime maximum temperatures in hot dry climates. In the hot dry summer of Seville (37°N), Spain, Coronel and Alvarez (2001) compared deep canyons in the city centre with the above-roof temperature outside the city centre. By night, they found that the streets were warmer by 2–3°C, while during daytime, the deep street canyons were 4–8°C cooler. In the hot dry desert city of El-Oued (33°N), Algeria, Bourbia and Awbi (2004) compared the temperature differences between one traditional and one contemporary neighbourhood. For the summer period, they found that the streets in the traditional neighbourhood (H/W ≈ 1.5–2) were slightly warmer by night and 5–6°C cooler by day than the streets in the contemporary neighbourhood (H/W ≈ 0.5–0.6). In their study of the microclimate in the hot dry desert village of Beni-Isguen (32°N), Algeria, Ali-Toudert et al. (2005) also found that the daytime maximum temperature decreased with increasing H/W ratio, although the variation was rather small (2–2.5°C), despite extensive variation in average H/W ratios from 0.1 to 6. One possible explanation suggested by the authors is that the deepest canyon (H/W = 6) was situated close to the city boundary and was thus affected by the much warmer climate outside.

In the hot humid summer climate of Dhaka (24°N), Bangladesh, Ahmed (1994) found that daytime temperatures had a tendency to decrease with increasing H/W ratio. He found the average decrease to be 4.5°C when the H/W ratio increased from 0.3 to 2.8. Similarly, the importance of shade for air temperature was investigated by Nichol (1996) in hot humid Singapore (1°N). She found significant differences between shaded and open places - where the ground was shaded by either high-rise buildings or shade trees, the average daytime air temperature was 1.5–2°C lower than for non-shaded ground of concrete or grass.

In their canyon study in a hot dry desert climate, Pearlmutter et al. (1999) examined the influence of orientation on the canyon air temperature. They found that, by day the north-west oriented street was slightly (<1°C) cooler than the east-west oriented street. By night there was no difference between the canyons. In a similar climate, Bourbia and Awbi (2004) also found that during daytime the north-west oriented streets were 1–2°C cooler than the east-west oriented streets.

Computer simulations

Ali-Toudert and Mayer (2005, 2006) simulated the microclimate of the desert city of Beni-Isguen (32°N), Algeria using the computer programme ENVI-met (Bruse 2006). They found that during hot dry summer conditions, the temperature decreased by about 3°C when the H/W ratio increased from 0.5 to 4 and that north-south streets were slightly cooler than those oriented east-west. Their investigations were restricted to the summer season. Swaid et al. (2003) simulated air temperatures for Tel Aviv (32°N), Israel, using the CTTC model (Swaid and Hoffman 1990) and also found lower air temperatures for north–south than east–west streets.

Concluding remarks

Most studies show that nocturnal heat islands are generally smaller in tropical cities than in mid-latitude cities, particularly during the wet season. A likely reason is that wet soils in rural surroundings have similar thermal admittance (see Fig. 3.2) as urban surface materials (see e.g. Oke et al. 1991). By day, the urban areas may be warmer or cooler than their surroundings. The results on humidity are somewhat contradictory, but it appears that cities are moister by night than their rural surroundings.

A majority of the field studies on intra-urban variations show that the urban geometry has a significant influence on air temperature and that daytime maximum temperatures tend to decrease with increasing H/W ratios. However, the effect of street orientation on air temperature has proven limited. However, field studies in hot dry climates have been restricted to the warm season and only a few studies have been conducted in hot humid climates. The few existing simulation studies confirm the link between urban geometry and air temperature. The simulations have not included the effect of parameters such as surface reflectivity and the thermal mass of canyon surfaces.

4.2 Outdoor thermal comfort in tropical cities

Of existing investigations on outdoor thermal comfort in hot dry and hot humid climates, two types can be discerned: those only comprising theoretical calculations of thermal comfort (based on measurements or simulations of climatic parameters) and those consisting of field campaigns combining climate measurements (often combined with index calculations) and questionnaire surveys on subjective thermal sensation.

Calculated thermal comfort

Pearlmutter et al. (1999) compared the energy exchange of a cylinder representing the human body within and above an urban canyon with H/W = 1 in the hot dry Negev Highlands (31°N), Israel. Later Pearlmutter et al. (2005) used the same approach in a physical scale model placed in the open air with H/W ratios of 0.33, 0.66, 1.0 and 2.0. In the summer, they found that daytime energy gain diminished with increasing H/W ratio. Moreover, they concluded that street orientation is important: north-south oriented streets were significantly more comfortable due to more efficient shading of direct-beam radiation. Only results from the summer period were presented and none of the conventional comfort indices were calculated, which makes it difficult to compare the results with other studies.

Swaid et al. (1993) used the CTTC model (Swaid and Hoffman 1990) to simulate the relationship between street design and thermal comfort, expressed as the Index of Thermal Stress, in the warm Mediterranean summer climate of Tel-Aviv (32°N), Israel. They found that the thermal comfort was better for H/W = 0.5 than H/W = 1 as well as in north–south compared to east–west streets.

Ali-Toudert et al. (2005) and Ali-Toudert and Mayer (2005, 2006) studied the relationship between street design and thermal comfort in the old desert city of Beni-Isguen (32°N), Algeria, by both measuring and simulating the microclimate. Extensive field measurements (Ali-Toudert et al. 2005) included eight streets and squares with different H/W ratios and orientations. The physiologically equivalent temperature (PET) was calculated after measuring all necessary environmental variables. PET was found to vary considerably, mainly as a result of extensive variations in mean radiant temperature (MRT). Both the MRT and the PET were found to decrease with increasing H/W ratio. In the afternoon, PET values were around 55°C for the open square (H/W = 0.1) and the shallow canyon (H/W ≈ 1) and around 40°C for the deeper canyons (H/W between 4 and 6), which provided shade. At around noon, not even the deep canyons could provide shade and values were high for all sites. However, the deeper canyons were found to have the advantage of shortening the duration of high PET values. An interesting finding was that the long-wave radiation absorbed by pedestrians exceeded the short-wave absorption and the authors stress the importance of shading the walls in order to reduce surface temperatures. The simulations (Ali-Toudert and Mayer 2005 and 2006) using ENVI-met (Bruse 2006) confirmed the measurements as regards the relationship between PET and H/W ratio. They pointed out that MRT decreases much more than the air temperature as the H/W ratio increases. Additionally, they found north-south streets to be more comfortable than east-west streets and that PET was lower under colonnades and shade trees than in non-shaded parts of the urban canyon. Finally, they suggested that streets be oriented northeast-southwest or northwest-southeast to achieve a favourable compromise between summer comfort and solar access in the winter.

Questionnaire surveys of thermal sensation

In his summertime field study in hot humid Dhaka (24°N), Bangladesh, Ahmed (2003) recorded subjective thermal sensation votes and measured environmental variables. He found comfortable conditions at considerably higher temperatures and levels of relative humidity than normally accepted indoors in temperate climates. The reported comfort zone is 27.5–32.5°C, where, however, the upper limit decreases for relative humidity levels exceeding 75%. Moreover, he concluded that semi-enclosed spaces, where air movement is restricted but where shade is provided, were sometimes perceived as comfortable during the hottest period of the day. This is contradictory to the common belief that the most important design strategy in the hot, humid tropics is to provide air movement.

Ahmed (2003) also found evidence of the influence of psychological factors, such as adaptation, expectations and thermal history (see Section 3.2). For example, he found that both the temperature and relative humidity perceived as comfortable were higher after a longer stay in the same place and that office workers accustomed to a relatively cool indoor environment, perceived the outdoor environment as warmer than street traders did, who spent the whole day outdoors. However, Ahmed did not calculate a comfort index, which makes it difficult to compare the results with other studies.

Both Spagnolo and de Dear (2003) and Nikolopoulou et al. (2003) compared objective microclimatic measurements (and calculation of thermal indices) with the subjective thermal sensation votes of a large number of subjects in the warm-temperate climates of Sydney, Australia (34°S) and Athens, Greece (38°N) respectively. They found a discrepancy between the measured and calculated thermal comfort and subjective thermal sensation. In general, people accepted a wider range of thermal conditions than indoors. Both studies point out the importance of physical adaptation to the outdoor thermal environment, which includes seasonal variation in clothing, changes in metabolic heat through the consumption of cool drinks and changes in posture and position. Psychological factors, such as expectations and thermal history also explain the discrepancies. For example, when outdoors, people expect more climatic variation than indoors, and this may increase their tolerance.

Concluding remarks

The studies reviewed show that calculated heat stress diminishes with increasing H/W ratios, at least for H/W above about 1, and that the heat stress is lower for north-south oriented streets than east-west streets. However, the studies have mainly dealt with the summer season in hot dry and warm-temperate climates and no studies of this kind have been conducted in hot humid climates.

As regards subjectively perceived thermal comfort, the studies indicate a poor correlation with calculated thermal comfort indices. The studies conclude that the comfort range is wider outdoors than indoors. One of the field studies reviewed also indicates that shade may be sufficient to achieve acceptable thermal comfort in hot humid climates.

4.3 Models and tools predicting urban microclimate

This section is mainly on numerical computer models that predict microclimatic parameters, but some other models and tools are treated briefly.

Numerical models

A large number of numerical models predicting different urban climate variables have been developed. In the choice of models and tools for this review, the emphasis has been on those predicting micro-climate variables such as temperature, humidity, radiation and wind speed within the urban canopy layer. However, pure wind simulation models based on advanced computational fluid dynamics (CFD) have not been reviewed although they are accurate and useful tools (see e.g. Tablada de la Torre 2006). The reason is that most CFD programmes are complex and require a high level of expertise. Local and meso-scale models dealing with entire urban areas and cities have not been considered.

ENVI-met

ENVI-met is a computer programme that predicts microclimate in urban areas (Bruse 2006). It is based on a three-dimensional CFD and energy balance model and is described in detail by Bruse (1999). A comprehensive summary of the model is also provided by Ali-Toudert (2005). See also Paper IV.

The model takes into account the physical processes between the atmosphere, ground, buildings and vegetation and simulates the climate within a defined urban area with a high spatial and temporal resolution, enabling a detailed study of microclimatic variations. The horizontal model size is typically from 100 m × 100 m to 1000 m × 1000 m with grid cell sizes of 0.5–5 m. The fact that the programme requires limited input data and that the modelling of the urban area is simple, makes it user friendly.

The input data consist of the physical properties of the urban area of study and limited geographical and meteorological data. The required input data for the buildings are dimensions, reflectivity, U-value and indoor temperature. Reflectivity and U-value are the same for all walls and roofs and the indoor temperature is constant and the same for all buildings. The model uses detailed data on soils, including thermal and moisture properties. Both the evapotranspiration and shading from vegetation is taken into account.

The required geographical and meteorological input data are longitude and latitude, initial temperature and specific humidity of the atmosphere at 2500 m (upper model boundary), relative humidity at 2 m height, wind speed and direction at 10 m height, and cloud cover. The model provides a large amount of output data including wind speed, air temperature, humidity and MRT.

Despite being highly comprehensive, the ENVI-met model has a few shortcomings. A major limitation is that it does not take into account the thermal mass of building envelopes (thermal capacity is only included for the ground). This is a significant drawback as the heat storage of façades exposed to solar radiation is not taken into account. Another limitation is the fact that the indoor temperature of buildings has to be constant during the simulation period, which is not realistic for naturally ventilated buildings. Both of the shortcomings mentioned will affect the surface temperatures of façades and, consequently, mean radiant temperature and air temperature.

ENVI-met can be classified as a tool intended for research purposes, rather than for design applications, since it requires detailed knowledge of urban climatology to be used properly. It has been successfully applied to a number of urban areas in a wide range of climates (see e.g. Lahme and Bruse 2004, Ali-Toudert 2005, Ali-Toudert and Mayer 2005, 2006, Jansson 2006 and Yu and Hien 2006). However, both Ali-Toudert (2005), who simulated the hot dry climate of Ghardaia (32°N), and Jansson (2006), who simulated the temperate climate of Stockholm (59°N), found that the programme underestimated diurnal temperature variations.

CTTC

The Cluster Thermal Time Constant (CTTC) model was developed by Swaid and Hoffman (1990) and calculates diurnal air temperature variation in an urban street canyon. The model uses the daily mean temperature, to which it adds a temperature increase due to solar radiation and subtracts a temperature reduction due to the net outgoing long-wave radiation. The solar addition term is based on the assumption that only the portion of the street heated by direct solar radiation heats up the air in the canyon. The solar term includes the empirical CTTC term, whose magnitude depends on the urban geometry. Although the model is simple, simulated results have agreed well with field measurements from the summer in Jerusalem (32°N) (Swaid and Hoffman 1990). However, according to Swaid and Hoffman (1990), the model is restricted to clear weather conditions and the summer season.

Elnahas and Williamson (1997) proposed further development of the CTTC model. Their modified model takes into account both diffuse and reflected solar radiation and uses hourly, rather than daily mean, values of the nearest weather station. This modified CTTC model, which also incorporates cloud cover and anthropogenic heat, has shown a good correlation with results measured in Sydney (34°S), Australia.

Later Shashua-Bar and Hoffman (2002) developed the Green CTTC model, which is a further development of the original CTTC model by Swaid and Hoffman (1990). The Green CTTC includes the effect of shade trees on canyon air temperature.

A major disadvantage with the original (Swaid and Hoffman 1990) and Green (Shashua-Bar and Hoffman 2002) CTTC models is that they are restricted to the summer season. The modified CTTC model by Elnahas and Williamson (Elnahas and Williamson 1997, Erell and Williamson 2006) may have wider applicability. However, another limitation with these models is that they are geometrically restricted to ordinary street canyons and only provide one parameter, the air temperature, as their output. Moreover, none of the models have, to the author's knowledge, been validated for climates other than those for which they were developed.

Other urban canopy layer models

A number of numerical models have been developed for the urban canopy layer based on the energy balance of urban surfaces and taking into account the thermal mass of buildings. These include, for example, the models of Mills (1997b) and Kusaka and Kimura (2004). A key disadvantage with these models is that they do not exist as user-friendly computer programmes and thus require a certain level of computational skill. Moreover, similarly to CTTC they provide few output variables and the modelling of the urban environment is very unrefined (either identical building dimensions and spacing or only a single canyon).

Models predicting solar radiation and surface temperatures

The RayMan computer programme (Matzarakis 2000, Matzarakis et al. 2000) is a tool for the calculation of MRT and thermal indices such as PET, PMV and SET*. To calculate MRT, the programme requires building geometry (length, width and height), information about trees (type, height, width of canopy), global solar radiation and cloud cover. The calculation procedure is described in detail in Papers I and III. RayMan's principal shortcoming is the uncertainty that exists regarding how it calculates surface temperatures. The programme does not require thermal properties, such as the thermal capacity and conductivity of the surfaces, and it is not possible to set different reflectivities for the street and walls. Nevertheless, it is reported that MRTs calculated using the programme have shown a good correlation with values measured in certain urban environments (Matzarakis et al. 2000).

The Solène computer programme simulates, among other things, short and long-wave radiation, as well as solar access and shade in urban spaces (CERMA 2006). It requires detailed geometrical information of the built environment, as well as material and surface properties. It calculates surface temperatures, making it possible to estimate MRT in urban environments.

TownScope (Teller and Azar 2001, Azar 2006) is a computer programme that, among other things, calculates solar access and shade in urban areas and on buildings. TownScope can also calculate thermal comfort expressed as the PMV index, although the accuracy could be questioned since meteorological input data is based on monthly mean values.

Other models and tools

Scale models

An alternative to field studies and computer simulations is to establish small-scale physical models. Scale models of this kind can be used to determine the effects of one or more variables on the urban climate. The best-known scale model regarding urban climate is the wind tunnel. Other scale models have investigated phenomena such as the nocturnal cooling of urban surfaces (Oke 1981), the relationship between urban geometry and indoor temperatures (Mills 1997a) and the solar absorption of different urban fabrics (Steemers et al. 1998). Some recent scale modelling, such as Kanda et al. (2005), Pearlmutter et al. (2005) and Pearlmutter et al. (2006), comprises comprehensive long-term measurements of several variables in models of built-up areas in the open air.

The main shortcoming of scale modelling is that it requires resources in space and time (the models are complicated to build up). Moreover, they often become expensive, which may explain why e.g. wind tunnel tests have rarely been performed in urban development. Consequently, physical scale modelling is generally more suitable for research than as a design tool.

Climatic maps

Climatic maps are graphical tools intended to help planners and urban designers. They exist in many different forms and scales, from regional to detailed planning levels (Lindqvist and Mattsson 1989, Katzschner 2000). At regional and land-use planning levels they provide climate information, helping determine where to build new urban areas. Maps aimed at the detailed planning level, i.e. the neighbourhood scale (scales 1: 5 000 or 1:1 000), typically show air flows around buildings, areas exposed to strong winds, thermally uncomfortable areas, duration of sunshine, heat islands, etc. (Lindqvist and Mattsson 1989, Katzschner 2000). Recently, thermal comfort maps of different scales (city, neighbourhood or public space) have been developed (Svensson et al. 2003, Katzschner et al. 2004). In these maps, a thermal index is calculated, making it possible to see which areas are more comfortable than others.

One shortcoming of climatic maps is that they seldom give detailed advice to planners. Their use requires some experience regarding climate issues and how climate data can be transformed into urban design principles.

Concluding remarks

There are few user-friendly computer programmes and tools that can predict the influence of urban design on the urban microclimate with good precision. Existing programmes tend to be either too complicated or their output is too limited. In this study, ENVI-met was considered the most appropriate tool for the simulation part of the study (see Section 5.2 and Paper IV). Despite certain shortcomings, it is one of the few numerical models in which a detailed modelling of the urban environment is possible and which provides detailed microclimatic output. RayMan was used to calculate MRT in this study (see Section 5.1 and Papers I and III) in spite of the possible inaccuracy in determining surface temperatures.

4.4 Urban design guidelines for tropical climates

Several studies include guidelines for climate-conscious urban design, both for hot dry and hot humid climates (e.g. Givoni 1992, Swaid 1992, Emmanuel 1993, Golany 1996, de Schiller and Evans 1998, Givoni 1998, Aynsley and Gulson 1999, Emmanuel 2005a). These guidelines cover a wide range of aspects, such as street orientation, urban form, shade in public spaces, surface material properties and building types. Many of the guidelines also cover aspects such as the choice of location and the use of green areas, although these are not treated here.

Guidelines for hot dry climates

The urban design guidelines for hot dry, and similar, climates that have been studied are included in Givoni (1992 and 1998), Swaid (1992), Golany (1996) and Grundström et al. (2003). As regards street orientation, the suggestions by Golany (1996) are in-line with solutions traditionally found in desert cities. He suggests narrow, winding, zigzagging alleys in order to create maximum mutual shading by buildings and claims that deep canyons of this type provide both solar protection during the day and remain warm during the night. Moreover, he claims that this street pattern provides good protection against warm and cold winds. Givoni (1998) argues that the orientation of streets is primarily related to access to, and protection from, the sun, whereas ventilation is of secondary importance in hot dry climates, since it is mainly needed at night. In contrast to Golany (1996), his opinion is that street orientation should encourage solar heating of buildings in winter and protect against solar radiation in summer. His solution to these virtually incompatible requirements is wide, east-west oriented streets ($0.5 \leq H/W \leq 0.7$) and narrow, north-south oriented streets ($3 \leq H/W \leq 5$). Similarly, Grundström et al. (2003) propose a blend of H/W ratios of 2, 1 and 0.7, where the lower H/W ratios are intended for east-west oriented streets.

As regards urban form, Golany (1996) suggests a compact urban form. He proposes that buildings be varied in height in order to maximize shade and suggests that public open spaces should be small, dispersed and well protected. According to Givoni (1998), an urban form should be chosen that both maximizes the shading of pedestrians and assures sufficient ventilation. Givoni (1992) argues that attached houses, such as terraced houses, are better than detached houses, since they have fewer walls exposed to the sun.

The above-mentioned guidelines emphasize the need for shade in urban public spaces, such as sidewalks and squares. According to Golany (1996), much of the shade is achieved by high H/W ratios. Givoni (1998), on the other hand, suggests shading of sidewalks by building details such as overhanging roofs, horizontal shading devices above the sidewalks or colonnades under projecting upper floors. A more unconventional approach is given by Swaid (1992), suggesting adjustable shading screens at roof level in the form of vertical screens (to increase building heights), overhangs and louvers.

These screens are intended to be used by day to increase shade and to be removed at night in order to increase the SVF to stimulate nocturnal cooling. Both Golany (1996) and Givoni (1998) promote shade trees, which also help cool the air through evapotranspiration, although the latter points out that planted areas require irrigation and may be expensive to maintain in hot dry climates.

Givoni (1998) stresses the importance of keeping surface temperatures low to reduce the energy absorbed by the urban fabric. This can be achieved through shading by buildings and by using vegetation, but also through high surface reflectivity. He argues that roofs in particular should use light colours.

Guidelines for hot humid climates

The urban design guidelines for hot humid climates that have been studied are included in Givoni (1992 and 1998), Emmanuel (1993 and 2005), de Schiller and Evans (1998) and Ainsley and Gulson (1999). As regards street orientation, Givoni (1992) emphasizes that this is of importance in densely developed rather than sparsely built areas. He argues that the optimum orientation of wide avenues is at an angle of 30–60° to the prevailing wind direction to enable the wind not only to penetrate into the city but also to provide cross-ventilation of individual buildings.

The guidelines studied agree that streets with long rows of closely spaced buildings perpendicular to the wind directions should be avoided as they may block the wind for entire urban areas. This is particularly important in coastal areas where the afternoon sea breeze can improve comfort conditions considerably. Consequently, urban spaces should, if possible, be aligned in the direction of the breeze. Aynsley and Gulson (1999) recommend that coastal urban spaces have a width at least four times the height of surrounding buildings. Moreover, they emphasize that required shading vegetation and shading devices should be located and designed to minimize resistance to breeze penetration.

As regards urban form, Givoni (1992) points out that compact urban areas have poor ventilation and high nocturnal heat islands. The authors agree that the best urban configuration in a hot humid climate includes dispersed high, slender buildings, preferably tower blocks or with the short end perpendicular to the wind direction. Aynsley and Gulson (1999) recommend that such towers, which could rise above a layer of two to three-storey buildings, should be spaced at least six tower widths apart. This urban form is also the most adequate for building ventilation and enables higher population densities. Givoni (1992), however, points out that such buildings are expensive to construct, operate and maintain.

For high-rise buildings, de Schiller and Evans (1998) recommend variations in height, irregular spacing and open passages at ground level in order to encourage the channelling of breezes, helping direct them to the pedestrian level. They propose a similar strategy for medium-rise buildings including variations in building height, form and spacing between buildings. For low-rise (one to two-storey) buildings de Schiller and Evans (1998) suggest courtyard buildings, whereas Givoni (1998) suggests detached houses. The former gives examples of how to group and design buildings to promote air movements for high, medium and low-rise construction.

The above-mentioned guidelines emphasize the need for shade in urban spaces, which can be achieved through shade trees, shading devices such as canvas screens, as well as colonnades for protection from the sun and rain. It is pointed out that shade trees should be tall with wide canopies, allowing them to provide protection against direct solar radiation at high solar elevations while permitting air movement at pedestrian level. Emmanuel (2005a), however, points out that finding space for trees in dense city centres may be problematic and that tree maintenance is often lacking. Contrary to the general concept of the majority of the guidelines that hot humid climates require a dispersed urban form, Emmanuel (1993) suggests more closely spaced buildings to enable shading. He proposes a method called “shadow umbrella”, which seeks to determine adequate building heights for shading purposes (Emmanuel 1993 and 2005a).

The guidelines studied point out the importance of shading the ground to keep surface temperatures low. To achieve this, they suggest using shading devices and vegetation. De Schiller and Evans (1998) also propose using colours that are as light as possible for façades and roofs to reduce solar absorption in urban surfaces. Emmanuel (2005a), however, points out the difficulty of keeping surfaces light in urban areas due to dirt and pollution. Moreover, he points out the risk of glare if excessively light surfaces are used.

Concluding remarks

To some extent, the existing guidelines are vague, since, with few exceptions, they do not define or quantify design aspects such as the space between buildings, building heights, H/W ratios, etc. In part, this probably is due to the fact that these guidelines are general for a larger region. De Schiller and Evans (1998) point out that their guidelines must be adjusted to local climatic factors and to other local conditions, such as topography, existing urban form and building traditions. However, the “vagueness” of the guidelines may also be a result of lack of research on the actual effects of urban design on the microclimate.

For hot humid climates, the majority of the guidelines reviewed argue for an open, dispersed city plan. This conflicts with the need in many tropical countries to increase population densities in cities.

4.5 Consideration of climate aspects in urban planning and design

This section reviews studies on the consideration of microclimate and outdoor thermal comfort in urban planning and design.

Good and bad examples of climate-conscious urban design

Examples of climate-conscious urban planning and design in developing countries in tropical climates are scarce. However, Evans and de Schiller (1990/91, 1996) report a few cases where microclimate aspects have been successfully implemented in urban design in Argentina. A project for the planned new Capital City included an urban design that provided wind protection and allowed for solar access, although this project was postponed. Moreover, the planning code of a municipality in the Buenos Aires (34°S) region was revised to allow tower blocks instead of a continuous street frontage along River Plate (Rio de la Plata) to encourage the sea breeze to enter the urban area.

Al-Hemaidi (2001) reports from a residential area in the hot dry city of Riyadh (25°N), Saudi Arabia, where climate-conscious design principles were successfully implemented. This was achieved by using a compact urban design with courtyard buildings without setbacks, oriented to maximize shade and wind exposure. Eben Saleh (2001) also reports from some recent, more compact residential areas in Saudi Arabia where a favourable microclimate was one of the priorities, although there is no information on the level of success of the concept.

However, many studies from warm countries report that climate issues are generally *not* considered in contemporary urban design. Both Al-Hemaidi (2001) and Eben Saleh (2001) report that current urban design in Saudi Arabia has led to an undesirable microclimate around buildings. They explain this with the prescription of an extremely dispersed urban design where the provision of shade is totally lacking. The current urban form is characterized by gridiron plans with wide streets where the detached, low rise “villa” is the most common type of house. Baker et al. (2002) report from a similar experience in hot dry Phoenix (33°N), in Arizona (USA): wide streets, dispersed low-rise buildings and oversized parking lots have contributed to urban warming. Bouchair and Dupagne (2003) found a similar situation in the Mzab valley (32°N), Algeria, where contemporary urban design lacks the microclimatic qualities of the traditional cities in the region.

Constraints for climate-conscious urban design

Urban planning is a complex field where different aspects have to be considered, including land-use, infrastructure, public transport, aesthetics, etc. Moreover, economy and politics strongly affect the planning process, which may have the effect that important urban design aspects are overlooked (Owens 1986, Evans and de Schiller 1996, Eliasson 2000). The microclimate is thus only one aspect in a planning process characterised by a multitude of often conflicting interests.

Several constraints that can explain the limited use of climate in urban planning have been identified. Both Evans and de Schiller (1996), in their study in Argentina, and Eliasson (2000), in her study in Sweden, found that necessary climatic investigations are often lacking in town planning projects due to budget and time constraints. Evans and de Schiller (1996) pointed out the lack of communication between climatologists and planners as a problem. Reports from climate consultants often describe only local climatic phenomena without giving any concrete advice to planners and architects on how to design the particular area.

Eliasson (2000) found evidence that climate had low priority in the planning process. Issues such as traffic safety and building design were considered more important. Moreover, she identified the lack of knowledge on urban climate as a major constraint, hampering planners' arguments in disputes on conflicting interests. She also found that the use of tools for climate-conscious urban design was limited.

Urban codes are often mentioned as a constraint for climate-conscious urban design. Severe problems caused by inappropriate building codes have been reported from hot dry climates. Al-Hemaidi (2001) and Eben Saleh (2001) both blame the poor outdoor comfort conditions in Saudi Arabian cities on Western-inspired planning codes. Baker et al. (2002) report a similar experience from Phoenix, Arizona, where current planning codes follow principles developed in cold climates and lacking requirements for shading.

Many of the world's urban codes have their roots in Western planning ideals from the first half of the 20th century. These planning principles, which were a reaction to the extremely poor sanitary conditions that existed in many Western cities during the 19th century and beginning of the 20th century (Pinson 1994, Bosselmann et al. 1995, Hall 2002), sought to guarantee "sunlight, fresh air and greenery" around buildings for health reasons. Distances between buildings were, for example, designed to allow for a sufficient number of hours of solar exposure per year (Pinson 1994).

Ways to incorporate climate issues in planning and urban design

Several studies discuss how climate issues can be better incorporated in the planning process. Evans and de Schiller (1996) urge the development of easily understood guidelines and design recommendations including the graphic presentation of urban design aspects. They claim that planners need guidance on factors such as building densities, maximum building heights and building forms.

Bitan and Potchter (1995), Evans and de Schiller (1996) and Eliasson (2000) all stress planners' need for guidance early in the planning process and the fact that climatic issues should be incorporated throughout the process. They point out the importance of establishing a dialogue between climatologists, planners, architects and others involved in urban development. Eliasson (2000) claims that if climate aspects are brought in late in the process, planners and architects tend to be unwilling to change their designs. Similarly, de Schiller and Evans (1998) emphasize that incorrect decisions at the town planning level are normally impossible to correct at a later stage. Ainsley and Gulson (1999) argue that outdoor thermal comfort should be a routine aspect of urban development and that climatic aspects should be included in urban codes at different planning levels.

Concluding remarks

The studies reviewed show that climate is rarely considered in urban planning and design and also indicate that codes and regulations are poorly adapted to local climatic conditions, often acting as obstacles to climate-conscious urban design. However, there are few studies from hot dry and, particularly, hot humid climates. Most of the studies stress the importance of increasing knowledge on climate aspects among urban planners and designers and of increasing cooperation between planners and urban climatologists during the entire planning process.

4.6 Conclusions

The main conclusions from this literature review are:

- Urban design has proved to have a considerable impact on urban microclimate in hot dry and hot humid climates. Outdoor thermal comfort generally improves with increasing H/W ratios in urban canyons due to increased shade.
- There are few user-friendly computer programmes aimed at predicting urban microclimate that provide both reliable results and detailed output.
- Urban design guidelines in hot dry and hot humid climates are often general in character and not always based on research. They need to be improved through specific guidance on design parameters, such as H/W ratio, orientation, surface properties and the spacing of buildings.
- Climate aspects are rarely considered in urban planning and design and urban codes are often poorly adapted to local climate conditions and may therefore hinder climate-conscious urban design.

However, although these topics have gained increased attention in tropical climates in recent years, the number of studies remains small, especially concerning hot humid climates and the cold season in hot dry climates.

This study seeks to bridge some of the gaps mentioned above by deepening the knowledge on how urban design influences the urban microclimate and outdoor thermal comfort through studies in the hot dry city of Fez, including both summer and winter conditions, and in the hot humid city of Colombo. The study tries to link measurements and simulations of the urban microclimate with an investigation of the role of climate aspects in the urban planning and design processes and an analysis of the effects of existing urban regulations on urban microclimate. The methods, results and discussion are presented in the following chapters.

5 Methodology

The research in this study is multidisciplinary in character. Its main objective is to understand how the physical characteristics of the built environment influence microclimate and thermal comfort in urban areas. However, the study also examines how climate-related issues are considered in the urban design and planning processes.

To provide responses to the research questions presented in Section 1.3, it was necessary for the design of the research process to combine various research methodologies. The overall design could be classified as experimental, although it includes a combination of the following *research methodologies*[1] (Groat and Wang 2002):

- Experiment
- Simulation
- Qualitative study.

In the combined approach of this thesis, the quantitative (experiment and simulation) methodologies dominate over the qualitative methodology. Within each methodology, different methods, or techniques, have been used.

The aim of the *experimental* part of this study was to map variations in microclimate and outdoor thermal comfort within each city. This entailed field measurements in areas with significantly different characteristics, including variations in urban geometry, ground cover and distance to the sea.

However, microclimate variation in cities is large and covering all differences would require extensive measurements. These would also be restricted to existing conditions in each city. The aim of the *numerical simulations* was to cover a wider range of urban design. Moreover, by using a simulation methodology, it is possible to isolate independent variables in order to determine their respective impact. It may also be possible to predict the effects of new urban design options on the microclimate and to optimize the design from a microclimate and thermal comfort perspective.

The possibility of implementing such design principles will, however, depend on current planning and design practices, awareness among professionals, design limits stipulated by urban codes and so forth. The aim of the *qualitative* part of the research was to obtain basic knowledge of the urban planning and design processes, including the role of climate and thermal comfort aspects.

The three methodologies were combined in different ways in order to obtain more reliable research results. For example, the physical and atmospheric processes governing urban climate are complex. This makes them difficult to simulate and the accuracy of existing models is sometimes questioned. Consequently, the experimental study was important in validating and calibrating the results of the

1 The term used by Groat and Wang (2002) is “research strategies”.

simulation study. The qualitative study was used to ascertain whether the optimum designs obtained from the simulation study complied with current regulations and current urban design practices. The mixed methodology also helped in identifying the strengths and weaknesses of existing urban codes with regard to climate-conscious urban design.

5.1 Experimental methods

The experimental part of the study, which is described in detail in Papers I, II and III, comprised measurements of climate variables in urban environments and estimations of outdoor thermal comfort. With a few exceptions, the measurements were performed within the urban canopy layer, see Fig. 3.1c.

The periods during which the experimental studies were conducted were timed to cover the seasons with the worst thermal stress. In the case of Fez, which experiences distinct climate seasons, both the hot dry summer and the cold winter periods were covered (see Fig. 2.2a). For Colombo, where annual climate variations are small, the climate measurements were conducted during the most thermally uncomfortable period, which is the inter-monsoon period in April–May (see Fig. 2.2b).

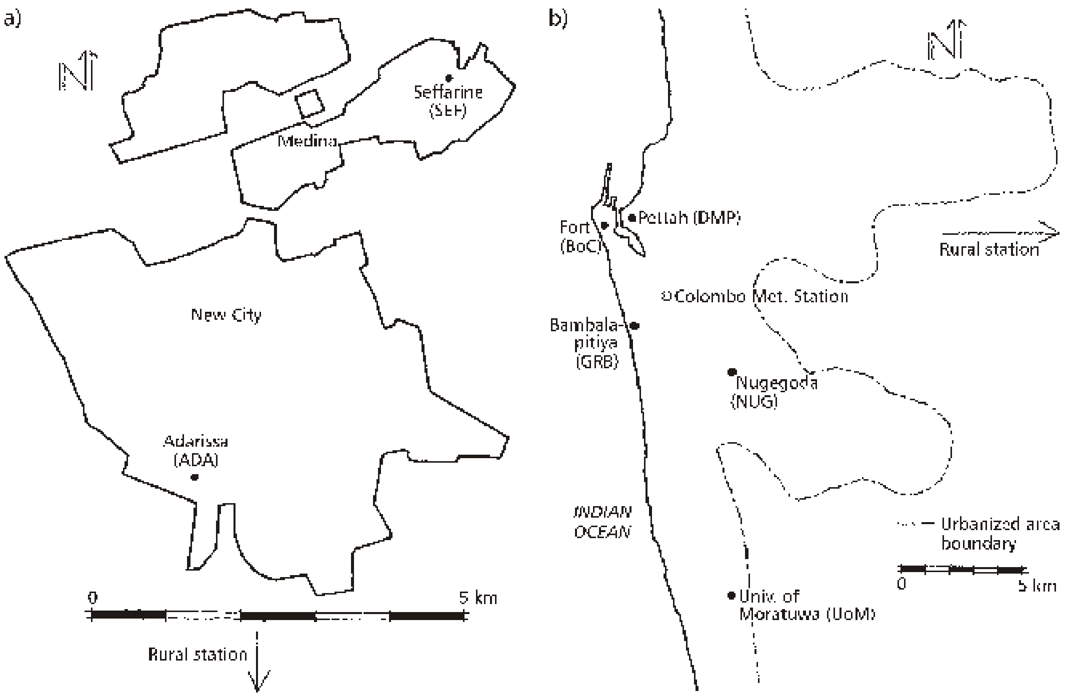


Fig. 5.1 The location of the measurement sites in (a) Fez and (b) Colombo.

Climate measurements in urban street canyons

Measurement sites

The testing environment consisted of a set of urban street canyons – two in Fez and five in Colombo. The location of the measurement sites within each city is shown in Fig. 5.1. These urban sites were compared with a rural station outside each city. In Fez, the climate at the official weather station[2], situated at Saïs Airport, about 15 km south of the city centre, was considered representative of rural conditions. In Colombo, measurements were taken in a rural area near Avissawella, some 30 km east of Colombo city centre.

The canyons were chosen to be representative of their respective neighbourhoods. The two canyons in Fez were completely different in terms of urban geometry (H/W ratio) and the amount of the ground covered by buildings. In Colombo, the differences in geometry between the five urban sites were significant, although not as great as in Fez. However, other parameters varied, such as the amount and type of vegetation, the type of ground cover and the proximity to the sea. The sites investigated in Fez are shown in Fig. 5.2 and described in detail in Paper I. The Colombo sites are shown in Fig. 5.3 and described in detail in Papers II and III. The characteristics of the urban canyons studied are shown in Table 5.1.

The thermal characteristics of the urban surfaces were similar for all sites in the two cities, comprising mainly dense materials, such as asphalt, concrete, brick and plaster. The predominantly impervious ground cover of the urban sites contrasted with the permeable soils in the rural surroundings. Whereas motor traffic was very limited at the two sites in Fez, it was intensive at some of the Colombo sites. However, since the impact of motor vehicles on the urban climate has proven to be very limited – except regarding air quality – it was not considered in this study. Similarly, anthropogenic heat was assumed to have an insignificant impact on the microclimate, since the heating and cooling of buildings and other heat-generating activities are limited in both cities.

Variables measured

- The variables measured were:
- Air temperature
- Surface temperatures
- Relative humidity
- Wind speed.

At each urban site, the temperature and humidity of the air was measured continuously with miniature data loggers, which were shielded against radiation. The loggers were placed at least 3 m above ground, because of pedestrian traffic and the risk of theft, and at least 1 m from the nearest façade. The measurements are assumed to be representative of the conditions at the pedestrian level, since temperature and humidity variations within urban canyons

2 Run by the Direction de la Météorologie Nationale, Morocco.

have proven to be small except near urban surfaces (Oke 2004). The complementary, instantaneous measurements of air temperature and humidity were taken at a height of about 2 m. In Fez, surface temperatures were measured both continuously and instantaneously, whereas in Colombo, only instantaneous measurements were taken. Wind speed was only measured instantaneously and on a limited number of occasions.

The parameters measured during each campaign are shown in Table 5.2 and the positions of the measurement probes are shown in Figs. 5.2 and 5.3. The type of equipment, as well as plans of the measurement sites, including the positions of the measurement probes, are presented in Paper I (for Fez) and Papers II and III (for Colombo).

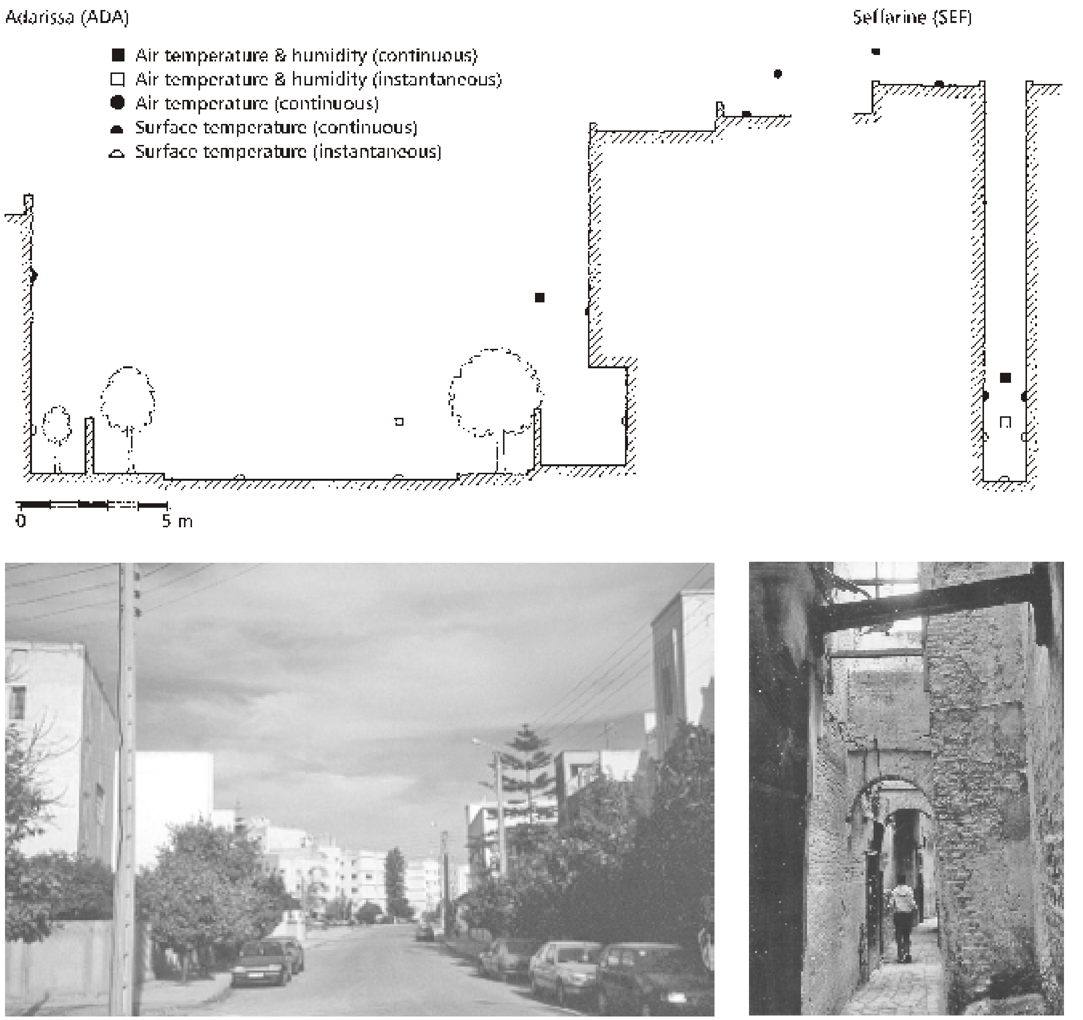


Fig. 5.2 The canyons studied in Fez and the positioning of the measurement probes.

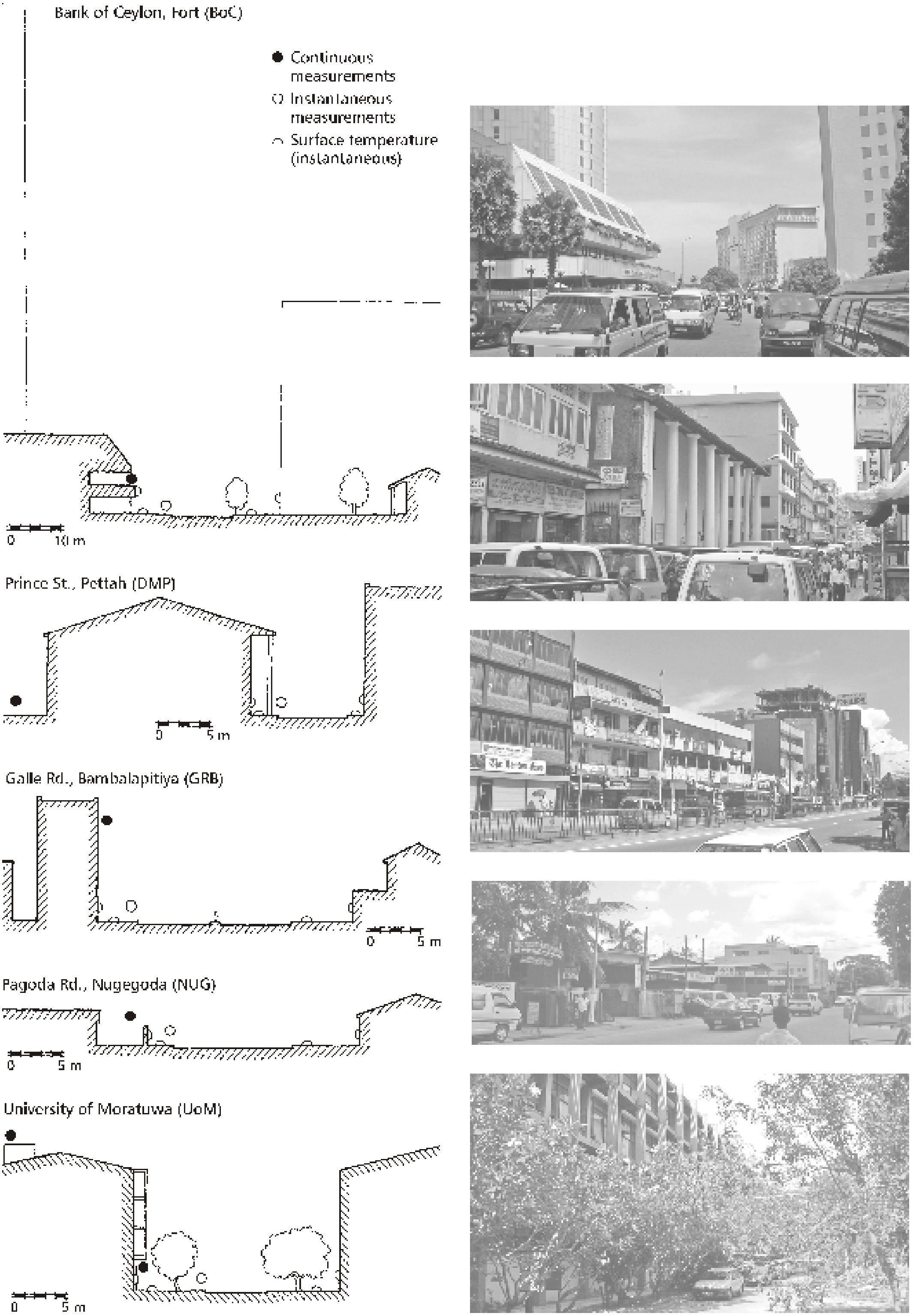


Fig. 5.3 The canyons studied in Colombo and the positioning of the measurement probes.

Table 5.1 The characteristics of the urban canyons studied and their immediate surroundings. The ground cover was estimated for a radius of 200 m around each site.

Site	*Key*	*General description*	*Land-use*	*Buildings*	*H/W*	*Dist. to sea (km)*	*Alti-tude (m)*	*Ground cover (%) Built-up*	*Roads, paving*	*Green*
Fez										
Adarissa, new city	ADA	Low-density suburb south of the city centre. Some small street trees.	Residen-tial	Medium-rise (2–3 storeys)	0.6	150	420	30	55	15
Seffarine, old city (the Medina)	SEF	Very compact neighbourhood in the heart of the old city. Deep canyons, devoid of vegetation.	Residen-tial (mixed)	Medium-rise (3–4 storeys)	9.6	150	280	80	20	0
Colombo										
Bank of Ceylon, Fort	BoC	City centre location (the central business district). Close to sea-shore, some trees.	Commer-cial/ office	High-rise, some very high towers	0.8	0.2	5	40	55	5
Prince Street, Pettah	DMP	High density city centre location, the old commercial quarters, just east of Fort. Away from the shore, almost devoid of vegetation.	Commer-cial/resi-dential	Medium-rise (3–4 storeys)	1.2	0.5	5	60	40	0
Galle Road, Bambala-pitiya	GRB	Commercial sector south of Fort, some trees. Close to sea shore, but buildings act as a barrier to sea breeze.	Commer-cial/ office residen-tial	Low to medium rise (3–4 storeys)	0.3	0.3	5	35	55	10
Pagoda Road, Nuge-goda	NUG	Mixed-residential sector south-east of the city centre. Few street trees, but green gardens. Away from the sea.	Residen-tial	Low rise	0.1	4	10	30	50	20
University of Mora-tuwa	UoM	Low-density, suburban location south of the city. High amount of green cover. Away from the sea.	Institu-tional	Medium rise	0.5	3	5	20	20	60

Table 5.2 The climate parameters measured during the measurement campaigns for the canyon studies. (T_a = air temperature, T_s = surface temperature, RH = relative humidity, W = wind speed).

City	*No. of sites*	*Continuous*	*Instantaneous*	*Time period*
Fez	2	T_a, T_s, RH		Feb. 2000–Aug. 2001
			T_a, T_s, RH, W	2–6 Feb. and 26–30 June 2000
Colombo	5	T_a, RH		30 April–12 May 2003
			T_a, T_s, RH, W	30 April–8 May 2003

The Fez study also included above-canyon measurements of air and surface temperatures. Moreover, additional instantaneous measurements were taken in canyons with varying H/W ratios and orientation within the two neighbourhoods studied during one summer and one winter week in 1998 (Rosenlund et al. 2000). In Colombo, temperature, humidity and global radiation above roof level were measured at the University of Moratuwa (UoM) site.

Definition of seasons and types of days

For the long-term measurements in Fez, the summer period was defined as the period from the end of May to mid-September 2000. During this 3.5-month period, the mean daily maximum temperature was above 30°C except for a few days. The winter period was defined as the three months with the lowest mean daily temperature: February and December 2000 and January 2001.

The two-week measurement period in Colombo in 2003 included a variety of weather conditions ranging from fairly clear days to overcast days, sometimes with rainfall. The measurement data were divided into clear, partly cloudy and overcast days and nights. In this study, the definition of "clear" was cloud cover of <5 octas, "partly cloudy" 5–7 octas and "overcast" >7 octas. For daytime conditions, these groups corresponded to the following daily global solar radiation ranges: >5000 Wh/m^2, 2000–5000 Wh/m^2 and < 2000 Wh/m^2 respectively.

Calculation of outdoor thermal comfort

Outdoor thermal comfort was estimated through theoretical calculations. The Physiologically Equivalent Temperature (PET) index, which takes all environmental factors influencing thermal comfort into account and is expressed in °C, was chosen for this study. The index is described in Section 3.2. The calculation of PET requires data on air temperature, vapour pressure, wind speed and mean radiant temperature (MRT). All of the necessary climatic variables were measured except certain radiation fluxes needed to calculate MRT. Vapour pressure was derived from air temperature and relative humidity.

For all canyons except the deep canyon in Fez (see Paper I), MRT was calculated using the RayMan 1.2 computer programme (Matzarakis 2000), which is described briefly in Section 4.3. The input data needed are global solar radiation (at pedestrian level), cloud cover and the urban geometry of the site.

In calculating global radiation at pedestrian level, it was necessary to take shading from buildings into account. For Fez, where no measurements of solar radiation were taken, global radiation was assumed to be equal to average values based on the period 1960–90 obtained using the Meteonorm software (Meteotest 1999). For Colombo, the unobstructed global radiation measured at the official weather station[3], situated centrally in the Cinnamon Gardens, was used (see Fig. 5.1). After dividing the global radiation into its direct S and diffuse D components, the global radiation at pedestrian level $K{\downarrow}_{street}$ was estimated as:

$$K{\downarrow}_{street} = S + SVF\quad D \tag{5.1}$$

where the sky view factor (SVF) is calculated at pedestrian level (1.1 m). This is a simplification, since reflected radiation from the

3 Operated by the Department of Meteorology, Sri Lanka

façades is not considered. However, such reflection is assumed to be limited compared to other radiation fluxes.

Each site was geometrically modelled in RayMan, including the size and position of buildings and trees. The reflected short-wave radiation from the street and the incoming long-wave radiation from the sky and urban surfaces was calculated using RayMan. The programme then calculates MRT according to VDI (1998), see Papers I and III.

Finally, PET was calculated using the RayMan software. However, the thermal comfort zone for PET in hot dry and hot humid climates has not been defined. In this study, the upper discomfort limit proposed by Ahmed (2003) for the summer in Dhaka, Bangladesh, see Section 4.2, which roughly corresponds to PET = 33°C (see Paper III), has been included as a reference for Colombo and the summer in Fez. The lower discomfort limit suggested for temperate climates – PET = 18°C (Matzarakis et al. 1999) – has been included as a reference for the winter in Fez. It should be noted, however, that this limit concerns a seated individual wearing typical indoor clothing (see Section 3.2).

5.2 Simulation methods

The simulation part of the study included computer simulations of the urban microclimate and calculation of thermal comfort.

Choice of model and calibration

Among the numerical models reviewed in Section 4.3, ENVI-met, version 3.0 was judged to be the most suitable for the simulation study. The programme is described briefly in Section 4.3 and in Paper IV.

One measurement site in each city was modelled in ENVI-met and the simulated microclimate was compared with the measured results. As a result of the deviation between measured and simulated results, input data, such as initial temperature, the humidity of the air and soil, as well as the thermal properties of the ground were adjusted. The magnitude of the solar radiation was also adjusted to agree better with the values measured.

The diurnal temperature variations were found to be underestimated by the programme for both the Fez and Colombo simulations. However, by lowering the wind speed in the Fez simulations from 2 m/s to 0.6 m/s, more realistic temperature fluctuations could be obtained (the reason being that the programme uses a different turbulence model at such low wind speeds). This manoeuvre did not work for the Colombo case. However, in Colombo, the diurnal variations are less and, consequently, the difference between simulated and measured variations was also less.

As mentioned in Section 4.2, ENVI-met 3.0 does not take into account the thermal capacity of the building envelopes. This was compensated for by increasing the thermal admittance (see Section 3.1) of the street. The effect of increased building density was included by increasing the thermal admittance of the ground with increasing H/W ratio.

The calibration for the Fez and Colombo cases is described in detail in Paper IV.

Parametric modelling

Model area and typified street canyons

The testing environment in the simulation part of this study was a street canyon (Fig. 5.4). The height of the buildings was kept constant at 12 m whereas the width of the canyon varied. In order to avoid influences from the ends of the canyon, the canyon was long, with a constant length-to-width ratio of 15, and with the wind always perpendicular to the long-axis of the canyon. The two buildings were enclosed by a wall of the same height as the buildings (12 m) in order to reduce the effect of advection from the surrounding "rural" area. The distance between the buildings and the wall was set equal to the width of the street (W). The reason for choosing a small model area was to limit the number of grids in order to restrict computation time. The area in Fig. 5.4a is to be seen as a part of a larger homogeneous area.

For each of the cities, a base case was created comprising a simplified urban canyon with typical geometric characteristics (H/W ratio), material properties, façade colours and ground elements. The input data of the base cases, which had no vegetation or shading devices, are shown in Table 5.3.

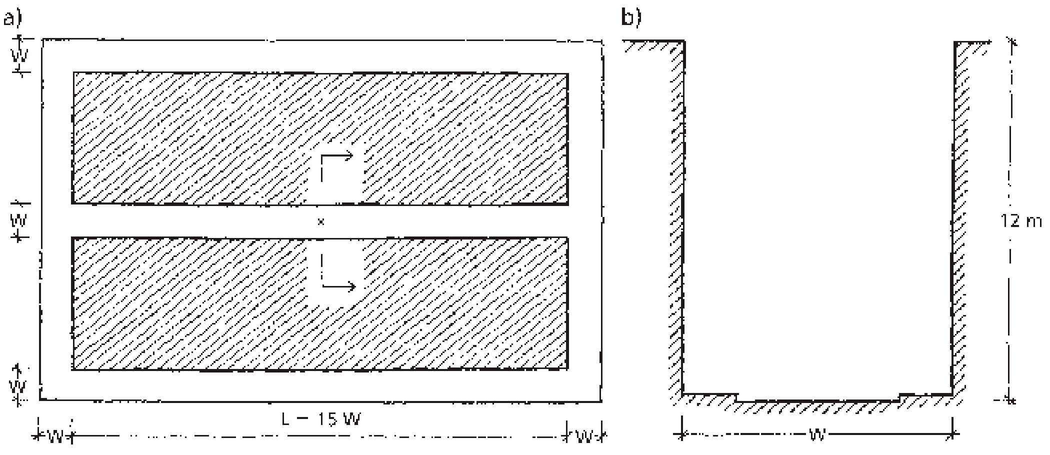


Fig. 5.4 (a) Model area and (b) the street canyon of the base case.

Table 5.3 Input data for the base cases in Fez and Colombo.

	Fez summer	*Fez winter*	*Colombo*
Building height, H (m)	12	12	12
Street width, W (m)	6	6	9
H/W ratio	2	2	1.3
Indoor temperature (°C)	26	20	26
U-value, walls ($W/m^2{}^\circ C$)	1.5	1.5	1.5
U-value, roof ($W/m^2{}^\circ C$)	1.5	1.5	1.5
Reflectivity, façades	0.3	0.3	0.4
Reflectivity, roofs	0.4	0.4	0.4
Reflectivity, street	0.3	0.3	0.3
Thermal admittance [a] μ, street ($J/m^2s^{0.5}{}^\circ C$)	4100	4100	3500

a Including the thermal admittance of the lower parts of the walls, see Paper IV.

Strategies for parametric modelling

The energy balance of a street canyon (see Fig. 3.6 and equation 3.5) was used to identify strategies to improve the microclimate of the urban canyons modelled for each city. If advection and anthropogenic heat are neglected, which is reasonable if the area studied is assumed to be sufficiently large and if buildings are neither heated nor cooled, sensible heat Q_H can be expressed as:

$$Q_H = K^* + L^* - Q_E - \Delta Q_S \qquad (5.2)$$

where K^* is the absorbed solar radiation, L^* is the net outgoing long-wave radiation, Q_E is the latent heat from evapotranspiration and ΔQ_S is the net heat storage in the canyon surfaces.

In a warm climate, such as that of Colombo and of the summer in Fez, the strategy to improve the microclimate would be to minimize sensible heat Q_H. In the daytime, the strategies will thus include:

- Decreasing absorbed solar radiation $K^* = K\downarrow - K\uparrow$. This can be achieved through increased shade (to reduce the incoming solar radiation $K\downarrow$), either by increasing the H/W ratio or by using shading devices or shade trees. By using light colours, reflected radiation $K\uparrow$ can be increased. It should be noted that a decline in K^* through additional shade will automatically reduce cooling through long-wave radiation L^*. However, since K^* is dominant over L^* during the daytime, the main strategy is to lower K^*.
- Increasing latent heat Q_E. This can be achieved by using permeable surfaces and vegetation to increase evaporation and transpiration. The increase in Q_E is particularly efficient in hot dry climates where evaporation is strong. However, as rainfall is scarce, abundant irrigation is necessary.
- Increasing heat storage ΔQ_S. This can be achieved by using heavy materials with high thermal admittance in façades and ground elements. It should be noted that a high daytime ΔQ_S may be negative in a climate with warm nights, such as that of Colombo, since the heat stored in urban surfaces during the day will be released after sunset.

The strategies for a cold climate, such as the winter period in Fez, would be the reverse of those proposed above, that is, to maximize Q_H. Consequently, it is necessary to identify a compromise between summer and winter requirements.

Similarly, the heat balance of the human body (equation 3.7) can be used to identify strategies to improve thermal comfort in different climates. In warm conditions, the heat loss through the evaporation of moisture diffused through the skin E_{dif}, as well as convective C_{res} and evaporative E_{res} heat loss through respiration are normally small compared to the other heat fluxes in the heat balance equation (see e.g. Höppe 1999). Consequently, the energy balance is maintained primarily through a balance between metabolic heat production M, convective and radiant heat losses ($C+R$) and the loss of heat through the evaporation of sweat E_{sw}. However, the latter may also be restricted in hot humid conditions, such as in Colombo, due to the high levels of humidity. Moreover, in warm climates, the sensible heat loss ($C+R$) is small and R can often be negative (radiative heat gain). It is therefore very important to maximize radiative and convective heat losses. Under warm conditions, the strategies to improve comfort conditions include:

- Increasing radiant heat loss (or minimising heat gain) R. This is achieved by lowering MRT, mainly through the provision of shade. Shade is needed both to minimize exposure to solar radiation and to lower surface temperatures. Surface temperatures can also be lowered through the use of lighter colours.
- Increasing convective heat loss C. This is achieved by increasing air movements.

In a cold climate, such as during the winter in Fez, the strategy would be precisely the opposite.

Parametric study

The simulations were performed as a parametric study in which different parameter characteristics of the urban canyons were subjected to adjustment. Only one parameter was changed at a time in order to determine the relative influence of each. The effect of the following design parameters on microclimate and thermal comfort were studied:

- H/W ratio
- Street orientation
- Reflectivities (colours) of ground and façades
- Thermal properties of ground materials
- Colonnades for shading of pedestrians
- Shading trees
- Wind corridors perpendicular to the street (Colombo).

The design parameters studied are shown in Table 5.4. The H/W ratios were chosen to reflect the measurement sites and the ratios commonly found in each city. Street orientation for all simulations was east-west. However, the north-south orientation was also studied for each H/W ratio. Reflectivity values represent realistic ranges, varying from dark to light façades, as well as from dark to medium-dark streets. As regards the effect of thermal mass, the lower thermal admittance value corresponds to light materials in the form of wooden façades and ground in the form of a light dry soil. The higher value corresponds to façades and ground of high density stone. The thermal admittance of the street has been enhanced by adding the thermal admittance of the lower parts of the façades, see Paper IV.

Table 5.4 The simulation cases for Fez and Colombo.

			Base case		
H/W ratio[a], Fez	0.5	1.0	**2**	4	8
Colombo	0.12	0.6	**1.3**	2	4
Reflectivity, façades		0.2	**0.4**[b]	0.6	0.8
ground	0.1	0.2	**0.3**	0.4	
Thermal adm., street ($J/m^2s^{0.5}$°C)	600	2500	**4100**	6500	
Colonnades			**No**	Yes	
Shading trees			**No**	Yes	
Wind corridors			**No**	Yes	

a Both east-west and north-south orientations were tested.
b The reflectivity of the façades was 0.3 in the base case for Fez.

The effect of colonnades was simulated according to Fig. 5.5. In both Fez and Colombo east-west oriented street with colonnades on both sides of the street was used. The effect of shading trees was simulated by placing a continuous row of trees along one of the façades in the base case, see Fig. 5.6.

As a final step, all of the changes found to improve the microclimate and thermal comfort at street level were combined to form a “best case” scenario. In the case of Fez, solutions were sought that could improve thermal conditions for both the summer and winter seasons.

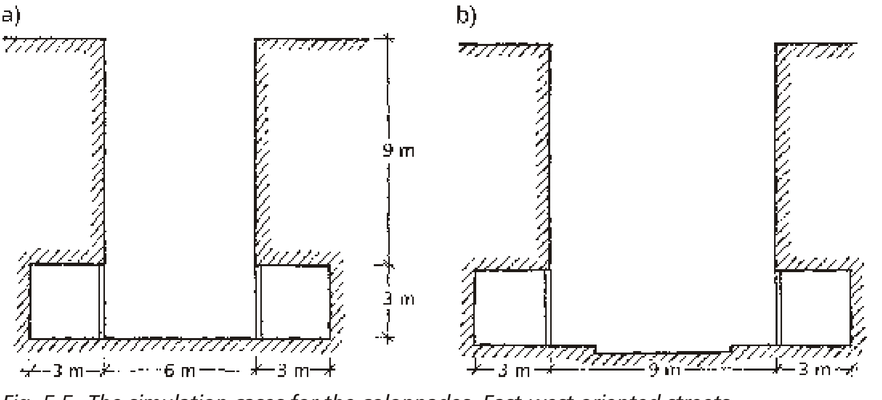


Fig. 5.5 The simulation cases for the colonnades. East-west oriented streets with colonnades on both sides of the street. (a) Fez, (b) Colombo.

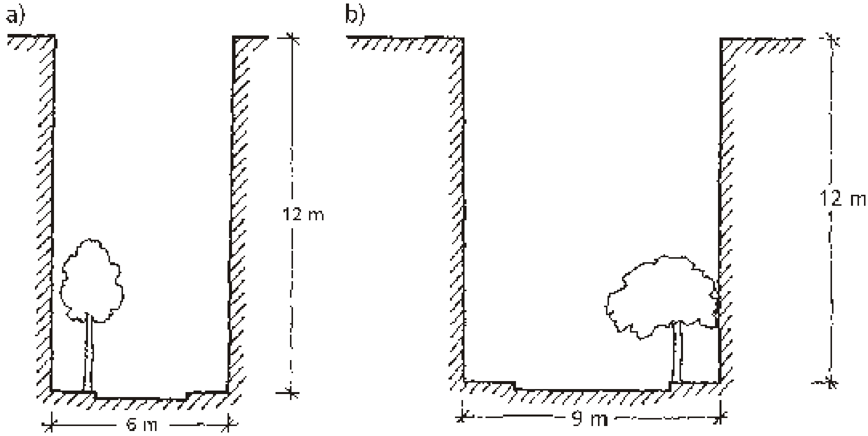


Fig. 5.6 The simulation cases for shading trees: (a) Fez, (b) Colombo.

Simulation of microclimate and calculation of thermal comfort

The simulations normally started at around sunrise and ran for at least 12 hours. The time step varied between two and ten seconds. The lower value was for high solar altitudes and the higher value for low solar altitudes and night time.

The Fez simulations were made for 15 January and 15 July. For these days, the solar radiation was adjusted to represent average conditions for the winter and summer periods respectively. The Colombo simulations were made for 3 May 2003, which was a “clear” day and representative of the most uncomfortable weather conditions (see Paper II). The PET index was calculated (see Section 5.1) on the basis of simulated hourly values for air temperature and MRT, as well as measured values for vapour pressure and wind speed as explained in Paper IV. The detailed output of the ENVI-met model, which gives the spatial variation of the climate parameters within the canyon volume, makes it possible to calculate how the PET index varies within the canyon (e.g. the difference in PET between areas in shade and areas exposed to solar radiation).

5.3 Qualitative methods

The qualitative study comprised an analysis of existing regulations related to urban design, as well as interviews with professionals involved in the urban planning and design processes.

Analysis of urban regulations

The documents studied consisted of regulations on urban design aspects, such as building heights, spacing between buildings and the portion of the ground permitted to be occupied by buildings. A list of the documents studied in Fez and Colombo is shown in Table 5.5. These documents have also been referred to in Chapter 2.

Table 5.5 The urban regulations studied in Fez and Colombo.

Document	*Year*	*Type of regulations*
Fez		
Land-use plan for the Wilaya of Fez (AUSF 1988)	1988	Zoning and building regulations
Land-use regulation of the walled medina of Fez (AUSF and ADER-Fès 1999)	1999	Building regulations
By-law concerning general regulations of road network and building (Ville de Fès 1969).	1969	Planning and building regulations
By-law concerning general regulations of road network and building (Ville de Casablanca 1952)	1952	Planning and building regulations
Colombo		
City of Colombo Development Plan. Volume I (UDA 1999a)	1999	Zoning regulations
City of Colombo Development Plan. Volume II (UDA 1999b)	1999	Planning and building regulations
Housing and Town Improvement Ordinance (Government of Sri Lanka 1980)	1980	Planning and building regulations

The main aim of the analysis of the urban codes was to find out which rules apply in each of the two cities studied. This included the following information:

- Zone types (residential, commercial, industrial, etc.)
- Building types in each zone (attached, semi-detached, detached, block, etc.)
- Maximum building heights
- Minimum street widths
- Maximum plot coverage
- Minimum setbacks
- Maximum floor area ratio (FAR).

The urban design regulations were translated into maximum H/W ratios for both the street and the backyards/courtyards. The urban regulations were analyzed to ascertain whether they facilitate or hinder climate-conscious urban design.

Interviews with people involved in urban planning and design processes

Interviews were held with urban planners, urban designers, urban developers and architects. The main aim of the interviews was to obtain information regarding the extent to which climate and thermal comfort aspects are considered in current urban planning and design. Another aim was to obtain general knowledge regarding the planning process in each city, which is important in being able to propose appropriate planning and design guidelines.

Informants were selected to represent professionals involved at different levels of the urban planning and design processes and included representatives of both the private and the public sectors. They consisted of senior officials at planning authorities, university teachers, private consultants in urban and architectural design and public and private urban developers.

In Fez, informants were selected through contacts with urban authorities in both Fez and Casablanca (Kursis 2001). The interviews and meetings with the informants were conducted as part of a cooperative project with the Laboratoire Public d'Essais et d'Etudes (Grundström et al. 2003). In Colombo, the key informants were selected in cooperation with the Department of Architecture at the University of Moratuwa. The number of informants representing different levels of planning and organization are shown in Table 5.6.

Table 5.6 Number of informants representing different levels of urban planning and design, as well as different organizations.

	Fez[a]	Colombo
Public authorities		
National planning		1
Comprehensive planning	1	1
Detailed planning	2	
Landscape planning		1
Private consultants		
Detailed planning/urban design		2
Architectural design	2	1
Urban developers		
Public urban developer	1	2
Private urban developer		1
Universities		
Town and country planning		1
Total	6	10

a Including one informant from Casablanca.

The interviews in Fez were performed during the period 1998–2000 and in Colombo in May 2003.

In Fez, the interviews were not structured and instead took the form of group discussions and personal meetings. In Colombo, semi-structured interviews (Widerberg 2002) were conducted. The aim of the interviews was to obtain information on the extent to which climate aspects are considered in urban planning and design, the information and tools used, the role of the urban codes, constraints for climate-conscious urban design, as well as the interest in and demand for climate-conscious urban design. The interview guide is shown in Appendix 3.

The analysis consisted of grouping the output from the interviews into themes from which conclusions could be drawn.

6 Results

The first two sections of this chapter present measurements and the results of calculations of outdoor thermal comfort. The third section shows results from simulations of the urban microclimate and thermal comfort. The final section deals with the results of the study on the consideration of climate in the urban planning and design processes in the cities of Fez and Colombo.

6.1 Microclimate measurements

This section summarises the results of the climate measurements in Fez and Colombo. The results are presented in detail in Papers I and II.

Microclimate in Fez

The results presented here derive mainly from long-term measurements in the "deep" and "shallow" urban canyons shown in Fig. 5.2 and described in Table 5.1. However, results from short-term measurements in the compact neighbourhood of Seffarine (in the ancient Medina) and in the dispersed, new suburb of Adarissa are also presented. The measurement campaigns are described in Section 5.1.

Seasonal urban–rural air temperature variations

The average temperature variations for the summer and winter periods defined in Section 5.1 are shown in Figs. 6.1a and 6.2 alongside the rural temperatures (Fez airport). The deep street canyon at the Seffarine (SEF) site had lower maximum temperatures than both the shallow canyon at the Adarissa (ADA) site and the rural site, both during the summer and winter. Conversely, daytime temperatures in the shallow canyon were similar to those of the rural site, being a few °C warmer in the summer period and about 1°C cooler in the winter period. During the night, both canyons displayed typical heat islands, whose intensity was greater in the deep canyon.

Intra–urban air temperature variations

In Figs. 6.1 and 6.2, it can be seen that the afternoon difference between the canyons was especially pronounced during summer. During the warm season, the difference in mean maximum daytime temperatures between the two canyons was 6°C, although the difference was even greater on hot, sunny days (Fig. 6.1b). During the winter period, the maximum difference between the canyons was only 3°C.

From the short-term, instantaneous measurements at five locations in each neighbourhood (see Paper I), it was found that the

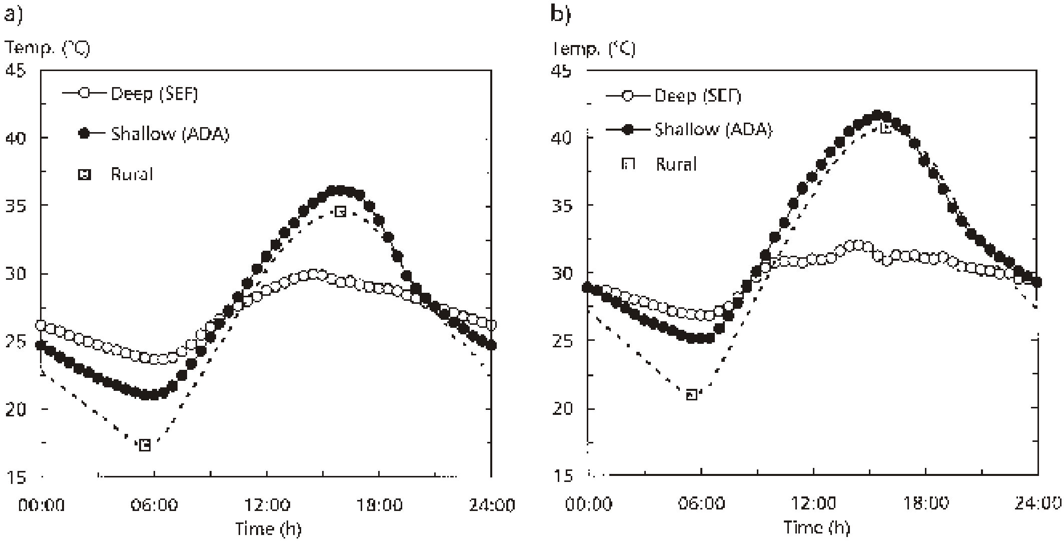


Fig. 6.1 Average temperatures for the canyons in Fez: (a) for the whole summer period and (b) for the 15 warmest days of the summer. (For site keys, see Table 5.1.).

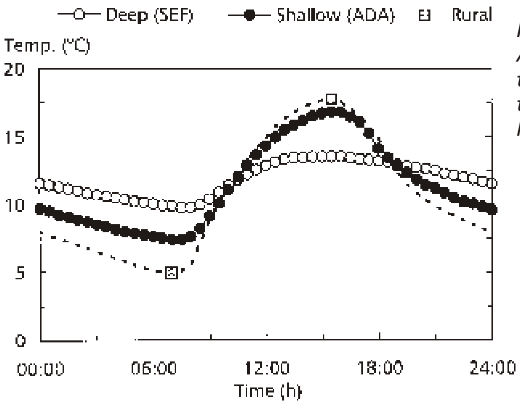


Fig. 6.2 Average temperatures for the canyons in Fez during the winter period. (For site keys, see Table 5.1.).

maximum air temperature tended to decrease with increasing H/W ratio. Consequently, in the compact neighbourhood in the Medina, a difference as great as 10°C was found between dense residential areas and the more open bazaar area, only 100–150 m away. In the suburban, dispersed neighbourhood, where all streets have a similar H/W ratio, the temperature differences were insignificant.

The short-term measurements did not reflect any significant influence from street orientation on air temperature in either neighbourhood.

Surface temperatures

While the surface temperatures of the façades of the deep canyon at the SEF site were stable, due to almost complete shade and low SVF, the shallow canyon at the ADA site showed extensive variation in surface temperatures depending on orientation, surface colour and height above ground. During the summer period, the maximum and minimum surface temperatures of the deep canyon façades were 28°C and 24°C respectively, and the street showed similar temperatures. In the shallow canyon, on the other hand, the temperatures of the light-coloured façades varied between 21 and 40°C, whereas the dark-grey street surface was the warmest with temperatures reaching 50°C. During the winter, the tendency was similar, although temperature fluctuations were smaller. Façade temperatures varied between 11 and 14°C in the deep canyon and between 7 and 23°C in the shallow canyon. However, lower portions of façades in the shallow canyon displayed lower maximum and higher minimum surface temperatures due to vegetation providing solar shading by day and preventing radiative cooling by night (see Fig. 5.2).

Humidity

Relative humidity was highly stable in the deep canyon at the SEF site but showed large diurnal variation in the shallow canyon at the ADA site, both in summer and winter (Fig. 6.3). Although relative humidity was higher during the winter period, the humidity in the air – expressed as vapour pressure – was lower (Fig. 6.3). Both in summer and winter, the deep canyon displayed higher vapour pressure than the shallow canyon, a difference that was particularly pronounced on summer afternoons.

Wind speed

The wind speed, which was measured instantaneously on three occasions per day, varied greatly from day to day and according to the time of the day. Wind speeds were lower and more stable in the deep canyon. The average wind speed in the deep canyon was 0.4 m/s during both the summer and winter measurement periods. The

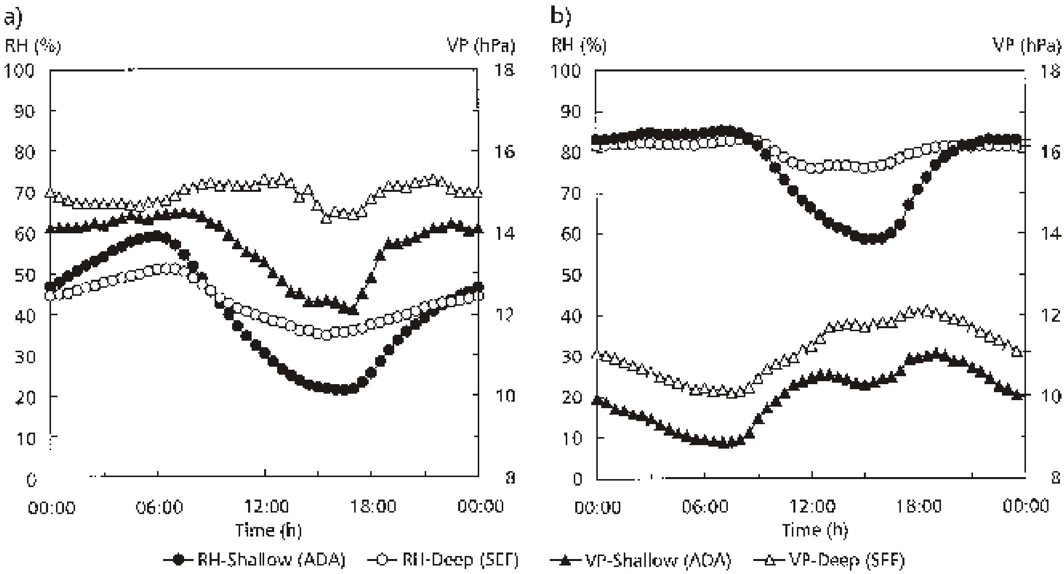


Fig. 6.3 Average relative humidity (RH) and vapour pressure (VP) in the canyons in Fez during (a) the summer period and (b) the winter period. (For site keys, see Table 5.1.).

shallow canyon had an average wind speed of 0.7 m/s in summer and 0.8 m/s in winter.

Microclimate in Colombo

The results presented here derive from the measurements in the urban canyons shown in Fig. 5.3 and described in Table 5.1. The measurement campaign is described in Section 5.1.

Urban-rural air temperature variations

The urban-rural air temperature differences during the measurement period were significant. Under clear conditions, differences were greater by day than by night. Fig. 6.4 shows the urban sites alongside the rural site on clear and partly cloudy days. On clear days, most of the urban sites were cooler (up to 4°C) than the rural station, whereas on partly cloudy days, the urban sites displayed maximum temperatures similar to those of the rural site (within ± 1.5°C). During clear and partly cloudy nights, a small, but distinct, heat island of about 3°C was able to develop (Fig. 6.6). There was a tendency for the heat island effect to diminish with increased cloud cover.

Intra-urban air temperature variations

The intra-urban differences were far greater by day than by night, especially on clear, days, but also on partly cloudy, days (Figs. 6.4 and 6.6). On clear days, the intra-urban difference reached 7°C. On overcast days, temperature differences between the fixed stations were negligible, which was to be expected since solar radiation is limited and the sea breeze weak.

Sites with higher H/W ratios, such as the Bank of Ceylon (BoC) and the University of Moratuwa (UoM) canyons, were significantly cooler than the shallow Nugegoda (NUG) canyon. The tendency for the maximum temperatures (here defined as the temperature at 14:00 h) to decrease with increasing H/W ratio on clear days is shown in Fig. 6.5. Although less pronounced, the same trend was also observed on partly cloudy days. During the night, there were small differences between the urban sites (Fig. 6.6). The relationship

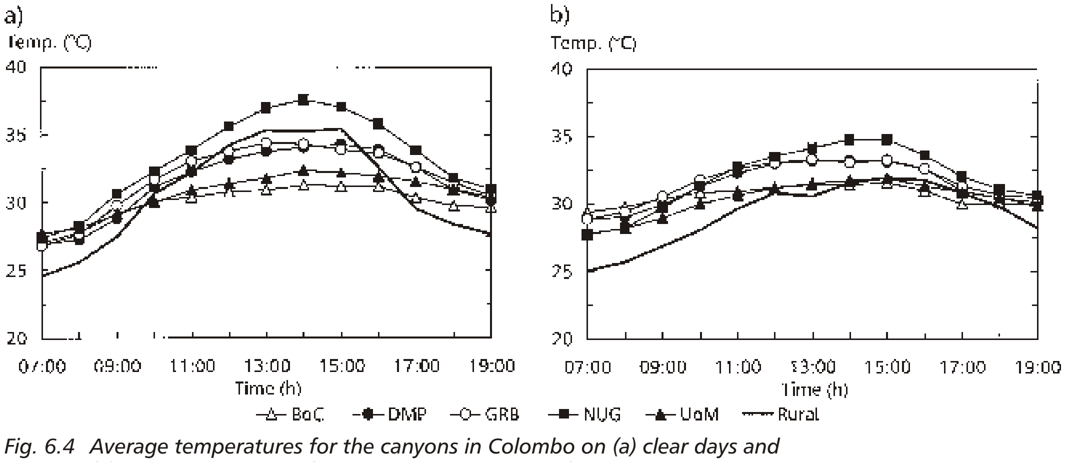


Fig. 6.4 Average temperatures for the canyons in Colombo on (a) clear days and (b) partly cloudy days. (For site keys, see Table 5.1).

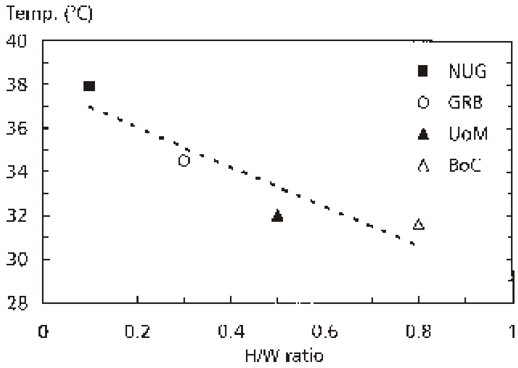


Fig. 6.5
The relationship between maximum daytime temperatures (at 14:00 h) and the H/W ratio in Colombo on clear days. (For site keys, see Table 5.1).

between H/W ratio and nocturnal heat islands was weak but towards the end of the night, just before sunrise (at 06:00 h), the tendency of increasing heat islands with increasing H/W ratio could be discerned.

The clearest evidence of the sea breeze effect can be seen by comparing the BoC site with the sites at Galle Road (GRB) and Pettah (DMP), see Fig. 6.4. All three sites are located roughly equidistant from the sea. Nonetheless, GRB and DMP are much warmer. The sea breeze is prevented from reaching these sites because they

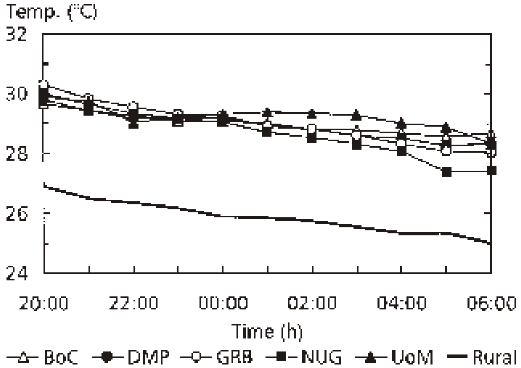


Fig. 6.6
Average temperatures of the Colombo sites during clear nights.
(For site keys, see Table 5.1).

are blocked by a continuous frontage of medium-rise buildings acting as a wind barrier. The sea breeze is also a factor contributing to the difference between the cool BoC site and the warm NUG site, which is about 4 km inland and not affected by the sea breeze.

The thermal properties of surface materials may also have contributed to the intra–urban temperature differences. For example, the only site where permeable ground existed (the gravelled road at the UoM site) was among the coolest by day. At the GRB and NUG sites, the maximum heat island was observed just after sunset. This may be attributed to the dense and dark surface materials, which absorb and store large amounts of heat during the day and release it after sunset. The phenomenon was particularly noticeable on nights following clear days with high solar radiation.

Surface temperatures

The surface temperatures of façades, sidewalks and streets varied considerably depending on orientation and surface colour. Under clearer conditions, horizontal surfaces, such as concrete paving and asphalt, which are fairly dark (i.e., having low reflectivity), displayed temperatures of between 50 and 60°C in the early afternoon. The temperature difference between sunlit and shaded areas located close to one another was between 10 and 20°C.

In general, façades were cooler than horizontal surfaces, especially around noon when differences reached 10–20°C. The reason was mainly because the angle of incidence was smaller, resulting in lower flux density of solar radiation. However, it should also be noted that some façades were of lighter colours than the streets and sidewalks. Nonetheless, under sunny conditions, façades were 5–15°C warmer than the surrounding air.

Humidity

The relative humidity varied between sites, but was, on average, around 75% during the daytime and around 90% at night. On clear days, however, the relative humidity dropped to 55% at the warmest sites (Fig. 6.7a). At the urban sites, vapour pressure at night was found to be slightly higher than at the rural site (Fig. 6.7b). During the day, however, vapour pressure was much lower in the urban areas. The observed positive nocturnal urban-rural vapour pressure difference agrees well with other studies which also found urban areas to have a moisture excess by night (Jáuregui & Tejeda 1997, Holmer & Eliasson 1999, Mayer et al. 2003).

Wind speed

Wind data reported from the official weather stations showed low wind speeds – averaging less than 2 m/s at the city station. The limited number of instantaneous measurements in the chosen street

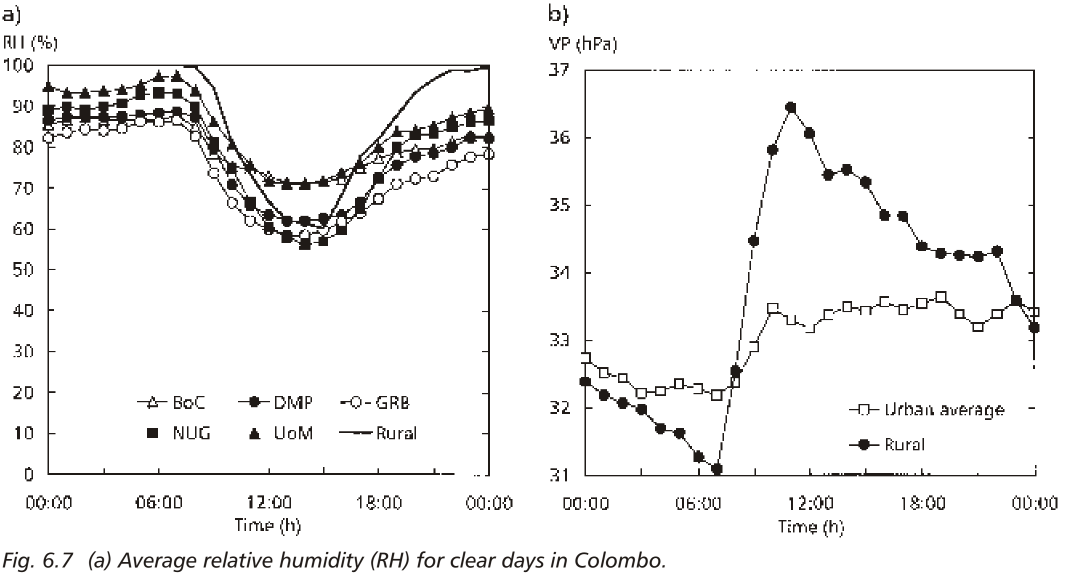


Fig. 6.7 (a) Average relative humidity (RH) for clear days in Colombo. (b) Average vapour pressure (VP) at the urban sites on clear and partly cloudy days compared with the rural site. (For site keys, see Table 5.1).

canyons indicated that wind speeds are higher in shallow canyons (NUG, GRB) and at the site open to the sea (BoC) than in the deeper canyons (DMP, UoM).

6.2 Calculated outdoor thermal comfort

This section provides results from calculations of thermal comfort expressed as the physiologically equivalent temperature (PET). The calculations, as well as the estimation of discomfort limits, are described in Section 5.1. The results are presented in detail in Papers I and III.

Outdoor thermal comfort in Fez

The calculated PET for the summer and winter periods defined in Section 5.1 are shown in Fig. 6.8 for a person standing in the middle of the street. In summer, the PET values in the deep canyon at the SEF site were very stable within a range of 23 to 28°C (the peak at 14:00 h is a result of the solar beam, which reached down to the street for a short period) and well below the assumed discomfort level of PET = 33°C. In contrast, the shallow canyon at the ADA site had PET values that were extremely high, exceeding the assumed discomfort threshold between 10:00 h and 18:00 h and reaching almost 50°C in the early afternoon. In winter, the deep canyon had low PET values, both by day and night, whereas the shallow canyon had very low values during the night but reached "comfortable" PET levels in the early afternoon. It should be noted, however, that the discomfort level concerns a sedentary person wearing indoor clothing. The level of discomfort will be considerably lower for a person wearing more clothing and/or being involved in a higher level of activity.

The large differences in PET between the canyons are mainly attributable to air temperature variations (see Figs. 6.1 and 6.2) and

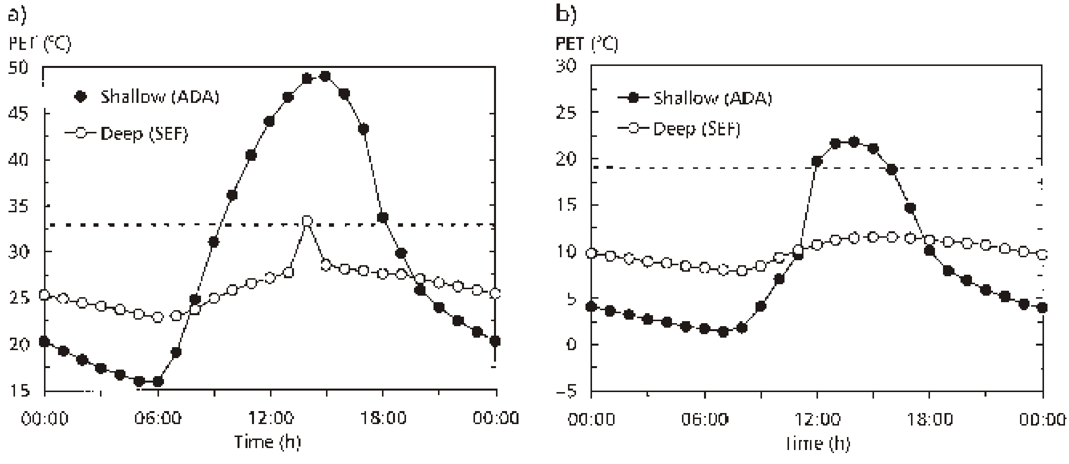


Fig. 6.8 Calculated PET in the middle of the street for Fez during (a) the summer period and (b) the winter period. The assumed upper (summer) and lower (winter) comfort limits are included as a reference (dashed lines). (For site keys, see Table 5.1).

mean radiant temperature (MRT). The latter is strongly linked to the H/W ratio. In the deep canyon, where people find themselves in almost constant shade during the day, with very little exposure to the cold sky vault, MRT varied between 25 and 28°C (except at 14:00 h, see Fig. 6.8a) in summer and between 11 and 13°C in winter. Conversely, there were extensive diurnal swings in MRT in the shallow canyon, where both incoming solar and outgoing long-wave radiation are strong, affecting not only people in the street but also the temperature of the canyon surfaces (see Section 6.1). During the summer period, diurnal MRT values varied between 16 and 63°C and, during the winter period, between 2 and 38°C.

The H/W ratio also influences the wind speed, but the difference between the canyons turned out to be rather small despite the extensive geometrical difference. The calculated PET values in Fig. 6.8 are based on the assumption that the wind speeds have constant values of 0.4 and 0.8 m/s in the deep and shallow canyons respectively (see Section 6.1).

Outdoor thermal comfort in Colombo

The calculated PET values for a clear day are shown in Fig. 6.9. In the calculations, the wind speeds from this day (3 May) have been assumed to be constant throughout the day, although measurements were taken on only a single occasion at each site (and not simultaneously). Fig. 6.9a shows PET for a person exposed to solar radiation (i.e. choosing to walk on the sunny side of the street). At all sites, values are above the assumed upper comfort zone limit between 11:00 h and 17:00 h. In the early afternoon, they far exceed this threshold, reaching 40-50°C. Fig. 6.9b shows the calculated PET values for someone choosing the shady part of the street (when shade exists). At several sites, this improves thermal comfort conditions considerably.

The main reason for extremely high daytime PET is the exposure to direct solar radiation. Intense solar radiation also results in temperatures of sunlit canyon surfaces being considerably higher than those of the surrounding air during clear and partly cloudy days. The sum of these two effects leads to high MRT, reaching values above 60°C in the early afternoon during clear weather conditions. MRT is linked to the H/W ratios of the urban canyons, but also to the position of the person within the canyon, i.e. whether exposed to the sun or in the shade. At most of the sites, the effect of shade on clear days can be seen as a sharp fall in PET (Fig. 6.9b). At the DMP and GRB sites, for example, PET drops by more than 10°C when shade is available. The effect is especially noticeable at the UoM site, where horizontal shading devices along the northern façade facilitate shade throughout the day. However, note that, around noon, none of the other sites provide sufficient shade because of the high solar altitude. At the NUG site, where the availability of shade is negligible, conditions are very poor throughout the day. Here, shade is available only in the early morning and late afternoon.

In a hot humid climate where weather conditions vary greatly, the magnitude of MRT is strongly related to sky conditions. Fig. 6.10

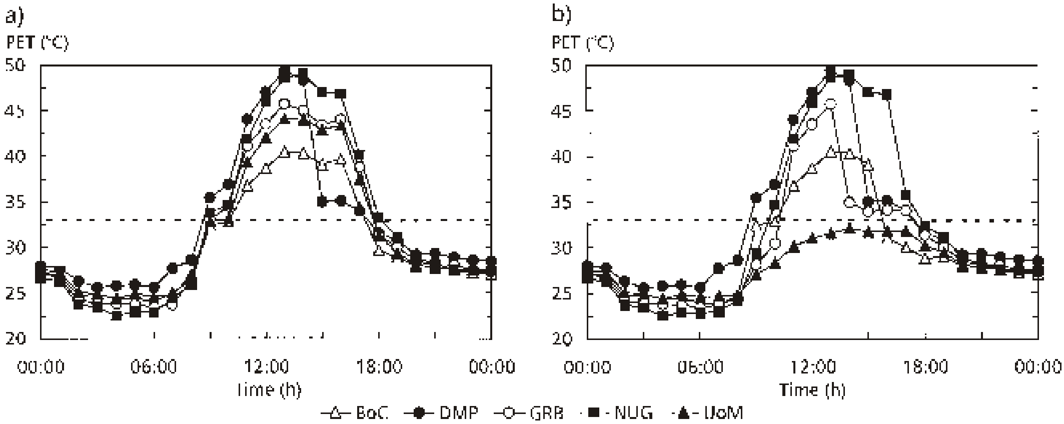
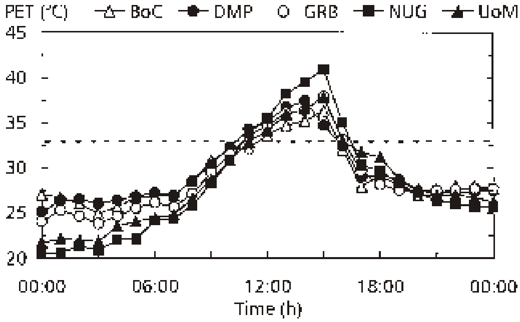


Fig. 6.9 Calculated PET on a clear day in Colombo (3 May 2003) for a person (a) exposed to solar radiation and (b) in shade, where available. The assumed upper comfort limit is included as a reference (dashed lines). (For site keys, see Table 5.1.).

Fig. 6.10 Calculated PET on a partly cloudy day (7 May 2003) for a person exposed to solar radiation. The assumed upper comfort limit is included as a reference (dashed lines). (For site keys, see Table 5.1.).



shows PET on partly cloudy days for someone exposed to the sun. On this day (7 May), only a few wind speed measurements were taken, but the relative difference between the sites was assumed to be the same as on 3 May. For the partly cloudy day, the differences in PET between the sites were smaller than under clear sky conditions (Fig. 6.9a). However, although the solar radiation was considerably less, the PET values were above the assumed discomfort threshold between 11:00 and 16:00 h. Consequently, shading will also have a positive effect during partly cloudy days. When the sky was completely overcast, and solar radiation weak, PET did not exceed the discomfort level and intra-urban variations were negligible, although areas with higher wind speeds tended to be more comfortable.

The sea breeze has a moderating effect on PET in that it lowers the air temperature. The effect of the sea breeze can be seen by comparing the BoC site, which is open to the sea breeze, with the GRB and DMP sites. The latter sites are also situated close to the sea, although the breeze is blocked by uninterrupted street frontages, resulting in poorer thermal comfort. The effect of wind speed can also be discerned in the PET results. For example, the compact urban form of the DMP site, with the highest H/W ratio, reduces wind speed, resulting in high PET values.

At night, PET is fairly low (Figs. 6.9 and 6.10). The lowest values were observed in the shallower canyons, which have the highest wind speeds and the highest levels of radiative cooling.

6.3 Simulations of microclimate and outdoor thermal comfort

This section presents the results from microclimate simulations using the ENVI-met software and subsequent calculations of thermal comfort. Only daytime conditions are considered. The results are described in detail in Paper IV.

Results from the parametric study

Once the model had been calibrated against the measurements (see Paper IV), the effect of the different design parameters described in Section 5.2 was studied. The area modelled and the street canyons studied are shown in Figs. 5.4–5.6. The results are presented as calculated PET, although the effects of H/W ratio and street orientation on air temperature are also presented.

Parametric study of Fez

Effect of H/W ratio and orientation

The relationships between the maximum daytime air temperature (defined as the temperature at 14:00 h) and the H/W ratio for both the summer and winter in Fez are shown in Fig. 6.11. For both seasons, the trend is for air temperature to decrease with increasing H/W ratio. In summer, daytime air temperature was found to peak for H/W ratios of about 1, see Fig. 6.11a. A sharp decrease in air temperature was found for H/W ratios of ≥ 2 in summer and for H/W ratios of ≥ 1 in winter.

In the summer case, the daytime temperature was found to be lower in canyons with a north-south orientation. This is because east-west oriented streets receive solar radiation during a longer period of the day. In the winter case, the east-west streets showed lower air temperatures than the north-south streets, although the difference was only about 1°C. For both seasons, the impact of street orientation is negligible for H/W ratios of ≥ 2.

Daytime PET values, calculated as average PET at pedestrian level (at 1.5 m height), for the Fez canyons are shown in Fig. 6.12 (summer) and Fig. 6.13 (winter). The assumed upper and lower comfort limits (see Section 5.1) are included for reference. During both seasons, and for both east-west and north-south oriented streets, the trend is for PET values and the duration of high PET values to decrease with increasing H/W ratios. However, for the same H/W ratio, north-south oriented streets are more comfortable than east-west oriented streets, during *both* summer and winter. The difference is most pronounced for H/W ratios of below about 4 since for higher H/W ratios the amount of solar radiation that reaches the street is small, regardless of orientation.

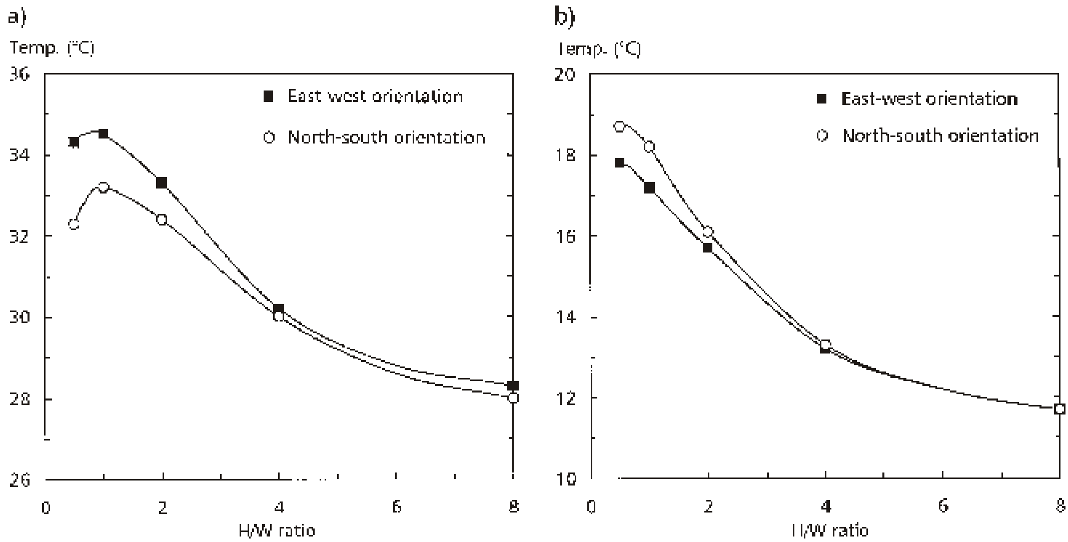


Fig. 6.11 Maximum daytime air temperature (at 14:00 h) as a function of H/W ratio in Fez for (a) the summer (15 July) and (b) the winter (15 January).

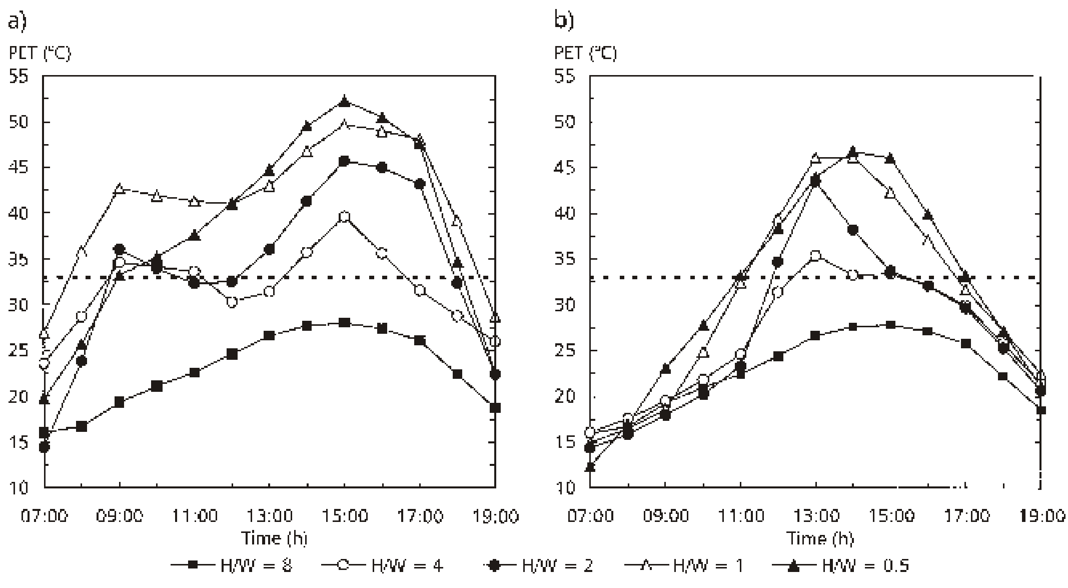


Fig. 6.12 PET at pedestrian level (average for the entire canyon width at 1.5 m height) for the different H/W ratios for the summer in Fez (15 July). (a) East-west oriented streets and (b) north-south oriented streets. The assumed upper comfort limit (dashed line) is included as a reference.

The peaks at 09:00 h and 15:00 h in the east-west canyon in summer are due to the fact that the sun is positioned due-east and due-west respectively at these times and, consequently, the entire canyon is exposed to solar radiation.

It should be noted that Figs. 6.12 and 6.13 show average values for the whole canyon width. In east-west oriented streets, for example, PET values on the northern side of the street will reach magnitudes

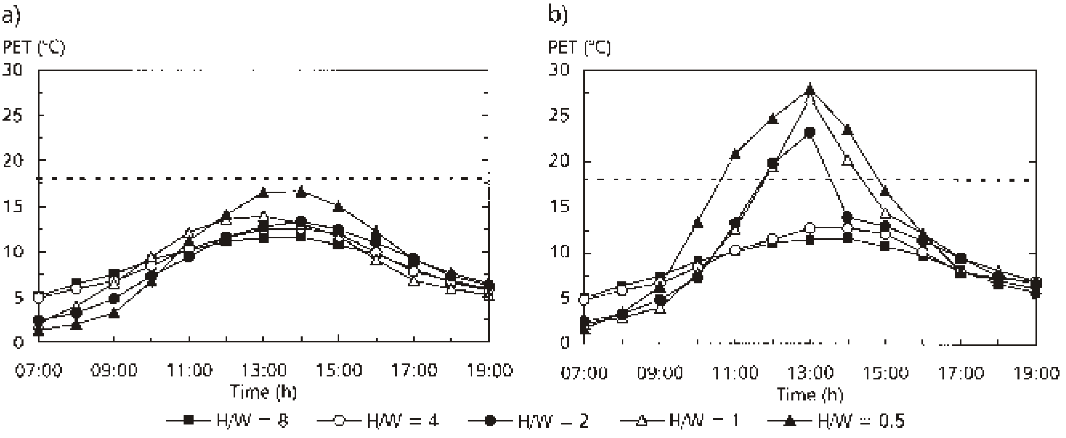


Fig. 6.13 PET at pedestrian level (average for the entire canyon width at 1.5 m height) for the different H/W ratios for the winter in Fez (15 January). (a) East-west oriented streets and (b) north-south oriented streets. The assumed lower comfort limit (dashed line) is included as a reference.

above 20°C during hours of solar exposure in the winter (see, e.g. Fig. 6.18b).

Effect of surface reflectivity

Surface reflectivity proved to have a minor effect on PET at street level. The difference in maximum PET between the cases with the highest and lowest reflectivity was 5°C in summer and 2°C in winter. However, what was unexpected was that the MRT (and consequently PET) *increases* with increasing reflectivity. This suggests that, in these simulations, the effect on MRT of increased reflection was greater than the effect of lower surface temperatures. This may be due to the fact that ENVI-met 3.0 does not take the thermal mass of the façades into account by. That is to say, the façades are unable to store the absorbed solar radiation. This has the effect that afternoon temperatures will be underestimated, particularly for dark surfaces.

Effect of thermal mass

PET tended to decrease with increasing thermal admittance μ of the street surface. This was expected, since the increased heat penetration into the substrate will lead to lower surface temperatures in the daytime (and consequently lower MRTs), as well as less sensible heat. However, the effect was greater for the summer case than for the winter case. In summer, the difference in maximum PET between the lowest and highest μ was about 8°C. In the winter, the difference was only 2°C. This is because less solar radiation reaches the street level in the winter.

Effect of shading at street level

The effect of shading by colonnades and a row of trees on maximum PET for the summer is shown in Fig. 6.14. It is clear that overhead shading significantly improves thermal comfort conditions. Beneath the colonnade, PET is about 18°C lower than in the centre of the canyon and just below to the assumed discomfort threshold (Fig. 6.14a). The row of trees is a little less efficient than a colonnade since the

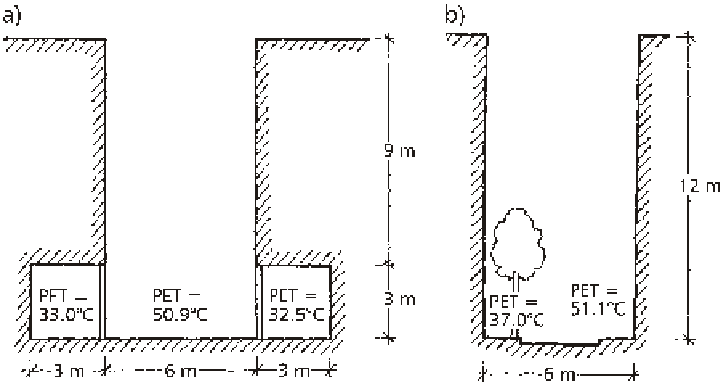


Fig. 6.14 Effect of shade on maximum PET (at 15:00 h) for the summer in Fez (15 July): (a) east-west street with colonnades on both sides, (b) east-west street with a row of trees along one of the façades.

tree canopies have some transparency. Beneath the trees, PET is about 14°C lower than in the centre of the canyon, but clearly above the assumed discomfort limit (Fig. 6.14b).

Parametric study of Colombo

Effect of H/W ratio and orientation

Contrary to the case of Fez, and contrary to measurement results, the simulated air temperatures varied only marginally between the Colombo cases. The simulated maximum daytime temperatures were about 32°C for all sites. The differences between different H/W ratios and street orientations were less than 0.5°C. This is probably due to the turbulence model used by ENVI-met, which differed from that used in the Fez simulations because of lower wind speeds, see Section 5.2. See also Paper IV.

Daytime PET (average value at a height of 1.5 m) for the Colombo canyons on a clear day is shown in Fig. 6.15. The assumed upper comfort limit (see Section 5.1) is included as a reference. As with the Fez summer case, the trend is for both PET values and the duration of uncomfortably high PET values to decrease with increasing H/W ratio. For very low H/W ratios (below 0.6), the influence of street orientation is marginal, but as the H/W ratio decreases, north-south oriented streets are more comfortable than east-west oriented streets. The former have lower maximum values and the duration of uncomfortable PET values is shorter than for the latter. To achieve a noticeable improvement in outdoor thermal comfort, east-west streets would need to be very deep, at least H/W = 4. For north-south oriented streets, a noticeable effect is seen for H/W ratios as low as about 2.

Effect of surface reflectivity

Surface reflectivity proved to have a minor effect on simulated maximum daytime PET at street level. As in the case of Fez, there is an unexpected tendency for PET values to *increase* with increasing reflectivity (see the comment on the Fez results above). For the Co-

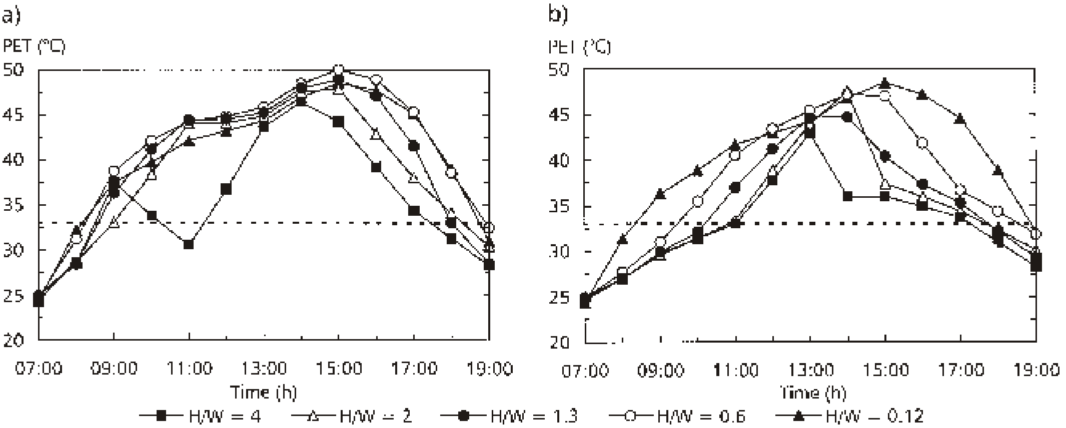


Fig.6.15 PET at pedestrian level (average for the entire canyon width at a height of 1.5 m) for different H/W ratios on a clear day in Colombo (3 May). (a) East-west oriented streets and (b) north-south oriented streets. The assumed upper comfort limit (dashed line) is included as a reference.

lombo case, the difference in PET between the darkest and lightest alternative was 2°C.

Effect of thermal mass

As in the case of Fez, PET tended to decrease with increasing thermal admittance ì of the street. However, the difference in maximum daytime PET was only 5°C between the lowest and highest ì value.

Effect of shading at street level

The effect of shading by colonnades and rows of shading trees on maximum PET is shown in Fig. 6.16. Maximum PET was about 10°C lower under the colonnades than in the centre of the canyon. Nonetheless, the simulated values are still higher than the assumed discomfort threshold. The trees are a little less efficient than a colonnade, since tree canopies provide some transparency and their ability to reduce PET was limited to about 7°C.

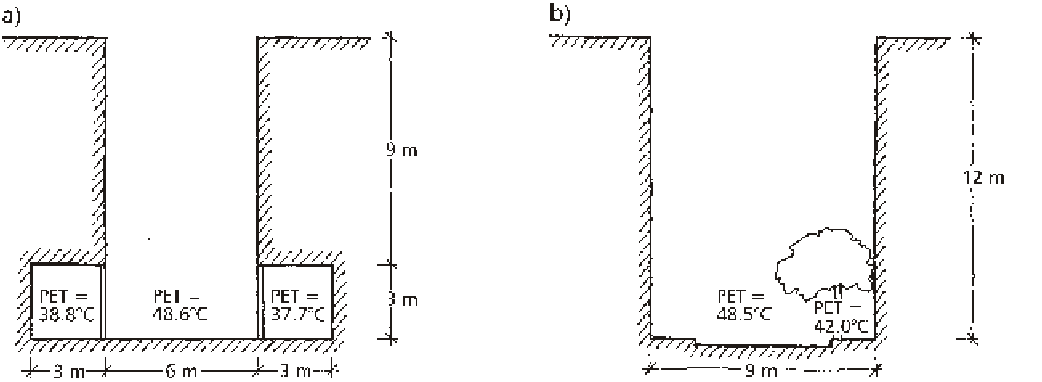


Fig. 6.16 Effect of shade on maximum PET (at 15:00 h) in Colombo (3 May). (a) East-west street with colonnades on both sides, (b) east-west street with a row of trees along one of the façades.

Effect of wind corridors

Although simulated wind speeds were unrealistically low, the opening up spaces perpendicular to the street canyon of the base case clearly led to increased wind speeds at pedestrian level. The simulated wind speed in the street more than doubled and at intersections, the wind speed was about twice of that in the canyon.

Optimised street design

The results of the parametric study showed that the H/W ratio, street orientation and provision of horizontal shading had the greatest influence on thermal comfort at street level. It was also shown that heavy building materials are favourable in a warm climate, whereas the influence of material properties proved to be negligible during the cold season in Fez. Since the ground surface and building materials most commonly used in both Fez and Colombo, such as asphalt, concrete, burnt clay bricks, concrete blocks and plaster, are already of medium to high density (see Fig. 3.2), the thermal admittance values used in the base cases were kept. Similarly, the reflectivity values of façades and the ground were not changed, since these proved to have an insignificant impact on thermal comfort in the simulations.

Optimised design for Fez

The fact that Fez has one warm and one cold season makes it difficult to optimise the design. What is a design advantage in the summer is normally a disadvantage in the winter. One way to overcome this problem is to combine streets that are comfortable in the summer with streets that show favourable winter characteristics.

The results from the parametric study showed that a street with favourable summer characteristics should have a high H/W ratio. However, the appropriate H/W ratio will depend on street orientation. North-south oriented streets should preferably have $H/W \geq 2$. East-west streets, on the other hand, need to be deeper ($H/W \geq 4$), to provide adequate shade in the summer. For lower H/W ratios than those suggested above, streets should be provided with some type of horizontal shading such as projecting first floors, colonnades, shading trees or other devices to provide shade around midday in summer.

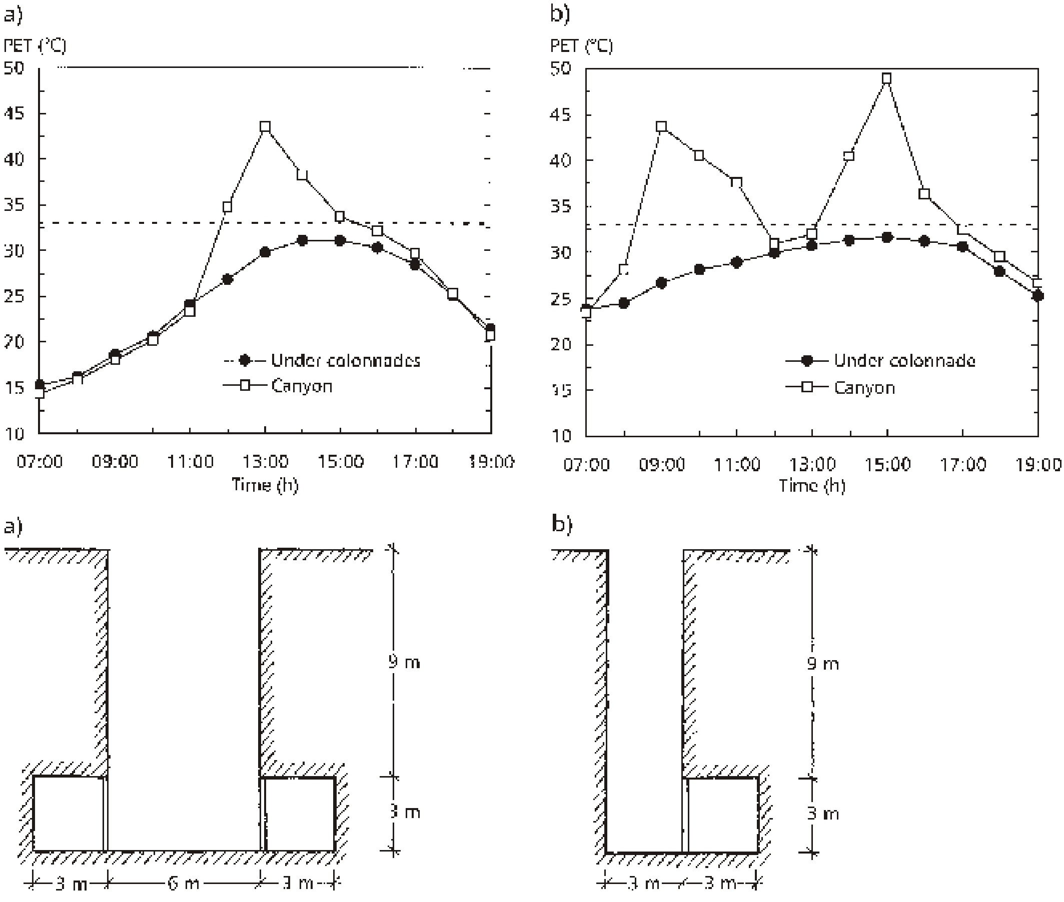


Fig. 6.17 Optimum design of street canyons for the summer in Fez. (a) North-south street of H/W = 2 with colonnades on both sides, (b) east-west street of H/W = 4 with a colonnade on the northern side. The graphs show the daytime PET variation for 15 July and include the assumed upper comfort limit (dashed line).

To achieve comfortable conditions in winter, east-west streets should have a H/W ratio sufficiently low to allow direct solar radiation to reach pedestrian level. If the H/W ratio is less than 0.7 and there is a colonnade on the northern side, solar access can be provided on that side of the street for a large part of the day during the winter months. Moreover, the colonnade will provide shade in summer. However, such streets should also preferably have some form of overhead shading, such as trees, on the southern side to improve the shade in summer. North-south oriented streets require a H/W ratio of ≤ 2 to provide some comfort in winter.

The various design considerations were combined to form “best cases”, presented as the street designs shown in Fig. 6.17 (summer) and Fig. 6.18 (winter). The daytime variation in PET for these canyons is also shown in the figures. North-south streets with H/W = 2 have been selected for both seasons since they constitute a compromise between summer and winter comfort. Colonnades have been added on both sides of the street to provide necessary shade in sum-

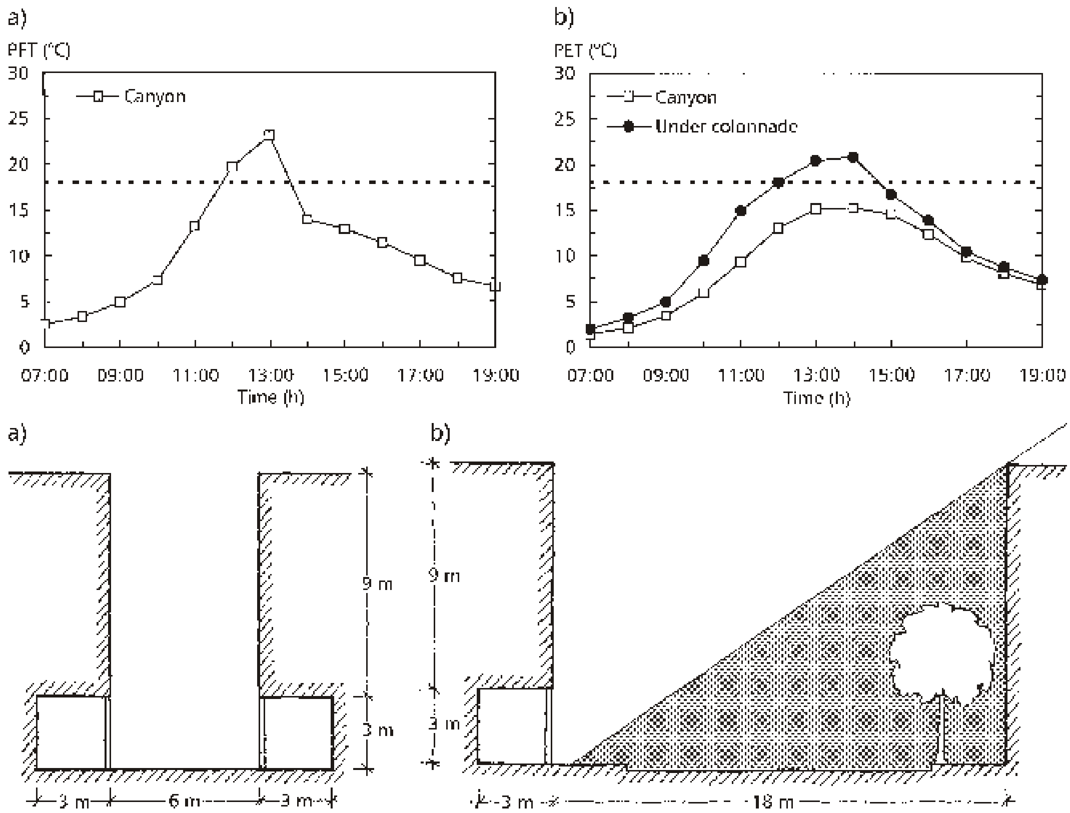


Fig.6.18 Optimum design of street canyons for the winter in Fez. (a) North-south street of H/W = 2 with colonnades on both sides, (b) east-west street of H/W = 0.67 with a colonnade on the northern side and a row of shading trees on the southern side (showing the solar exposure at around noon). The graphs show the daytime PET variation for 15 January and include the assumed lower comfort limit (dashed line).

mer during times of solar exposure. In winter, the north-south canyon of H/W = 2 reached “comfortable” levels around noon. The shallower east-west canyon of H/W = 0.67, which has a colonnade on the northern side, can provide “comfortable” conditions for a larger part of the day (between about 11:00 h and 15:00 h). This period will be slightly shorter in December but longer in February.

Optimised design for Colombo

As in the case of Fez, the parametric study showed that streets should have high H/W ratios to improve thermal comfort conditions. However, to achieve improved comfort conditions for street canyons oriented east-west, the most problematic orientation, H/W ratios would have to be as high as 4. North-south oriented streets should have H/W ratios of at least 2. Regardless of H/W ratio and orientation, streets in Colombo require horizontal shading – through projecting first floors, colonnades, shading trees or other horizontal shading devices – to improve comfortable conditions between about 11:00 h and 16:00 h.

In Colombo, it is also important to facilitate air flow. Consequently, long, uninterrupted street frontages are disadvantageous, since they block the wind. One way of providing shade and air movement is to use detached, rather high blocks, which would provide shade at street level and allow the wind to be channelled between the buildings. Buildings could also be varied in height and raised on columns to increase air movement at pedestrian level. Since the sea-breeze in Colombo comes from the west, a good strategy would be to allow fairly wide east-west oriented streets near the coast to maximise the penetration of the sea breeze.

Examples of optimum design for street canyons are shown in Fig. 6.19 (north-south orientation) and Fig. 6.20 (east-west orientation), including daytime PET variation for these canyons. It can be seen that a north-west oriented street with H/W = 2 and colonnades causes only slight discomfort during the hottest hours (12:00 h – 16:00 h). The case is very similar for the east-west oriented street of H/W = 4. The shallow east-west canyon (Fig. 6.20b) is assumed to be near the coast and therefore the wind speed was increased by 100% compared to the base case. Still the canyon is extremely uncomfortable. However, under the colonnades the comfort is much better, although it is above the assumed discomfort level between 12:00 h and 17:00 h.

a)

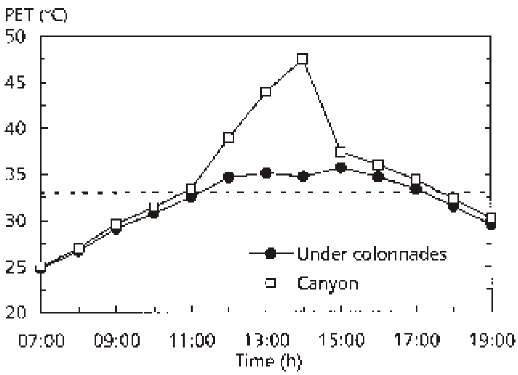
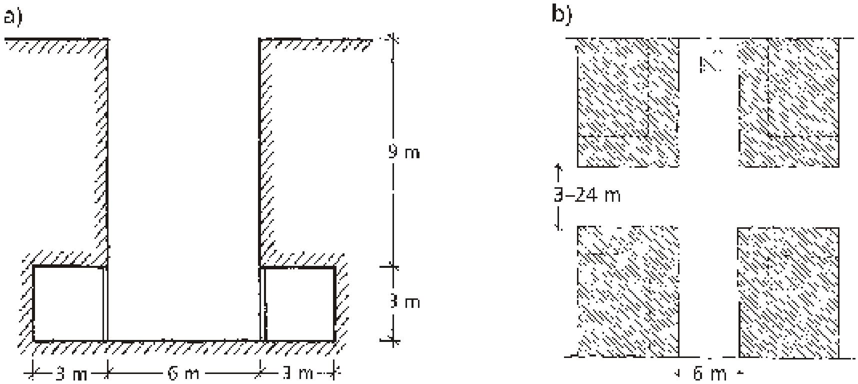


Fig. 6.19
Optimum design for a north-south oriented street in Colombo.
(a) Section of a canyon of H/W = 2 with colonnades on both sides. The graph shows the daytime PET variation for 3 May and include the assumed upper comfort limit (dashed line).
(b) Plan showing detached blocks allowing the westerly sea breeze to enter the street.

a) b)



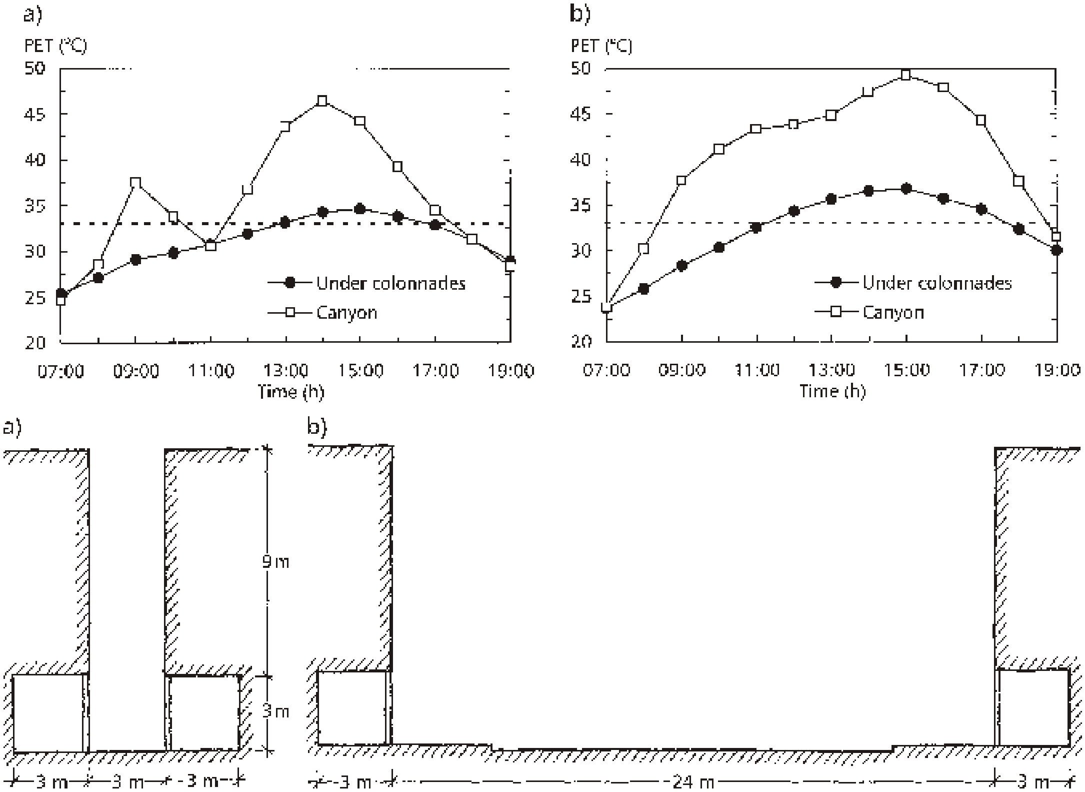


Fig. 6.20 Optimum design of east-west oriented streets in Colombo.
(a) Section of a canyon of H/W = 4 with colonnades on one side.
(b) A shallower canyon of H/W = 0.5, with a colonnade on both sides, designed to allow the westerly sea breeze to penetrate the city. The graphs show the daytime PET variation for 3 May and include the assumed upper comfort limit (dashed line).

6.4 Consideration of climate in the urban planning and design processes

This section presents the findings regarding the extent to which current urban planning and design practices in Fez and Colombo take climate aspects into account.

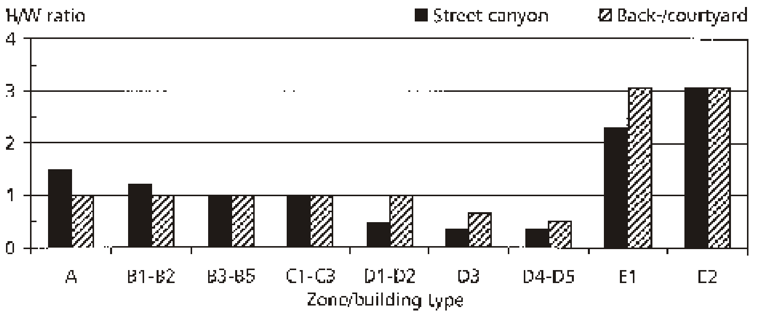
Influence of urban codes on microclimate and outdoor thermal comfort

The urban codes of the two cities have in common that they date back to the colonial period when Western planning ideals were introduced. Although some adjustments to the urban regulations in both Fez and Colombo have been made over the years since their introduction, the principles have remained the same.

Urban codes in Fez

H/W ratio, plot coverage and floor area ratio (FAR)

The regulations for the new city, which are described in Table 2.2, result in the urban geometry, expressed in terms of height-to-width (H/W) ratios, shown in Fig. 6.21. This figure shows the H/W ratios both for street canyons and back yards (courtyards), see Fig. 6.22. Streets have been assumed to be 10 and 4 m wide respectively for zones D and E[1].



A = Attached high rise blocks
B = Attached blocks
C = Detached slab blocks
D = Detatched. semi-detached and terraced houses
E = Low-income housing of neo-traditional style

Fig. 6.21 The maximum H/W ratios of the street canyons and back yards/courtyards for different housing types in the new city of Fez. (Calculated from AUSF (1988), assuming street widths of 10 and 4 m respectively for zones D and E).

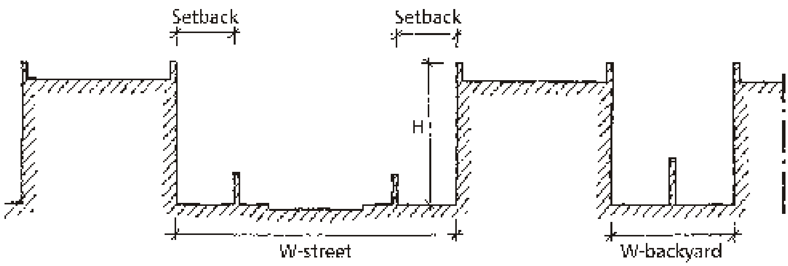


Fig. 6.22 Section defining the height and width of street canyons and back yards (courtyards).

In the historical Medina, the regulations described in Table 2.3 lead to the H/W ratios shown in Fig. 6.23.

It should be noted that the H/W ratios in Fig. 6.21 assume an average storey height of about 3.5 m. Were minimum storey height (about 3 m including the floor structure[2]) to be used, H/W ratios would be lower. It could also be the case that H/W ratios should be lower due to limitations of plot coverage and floor area ratio (FAR), see Table 2.2. Moreover, it should be noted that road widths in zone

1 The national decree of 1964 provides for street widths of 8 m for zone E1 and 12 m for zone E2. The code for Fez (AUSF 1988), on the other hand, does not prescribe any minimum street widths. However, it does state that where street width is less than 4 m in zone E2, the top storey must have a setback equivalent to at least half of the height of the building.

2 The minimum height, measured between the floor and the ceiling, is 2.8 m for living spaces and 4 m for ground floor shops (VF 1969).

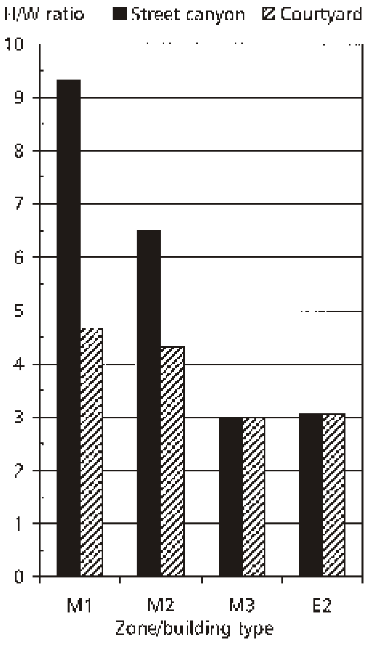


Fig. 6.23 The maximum H/W ratios of street canyons and courtyards for different housing types in the historical Medina of Fez. (Calculated from AUSF and ADER-Fèz (1999), assuming street widths of 1.5, 2, 2.5 and 4 m respectively for zones M1, M2, M3 and E2).

M1 = Traditional courtyard houses
M2 = Neo-traditional courtyard houses
M3 = Modern residential blocks
E2 = Low-income housing of neo-traditional style

E are often greater than assumed here, with narrow roads generally comprising pedestrian alleyways within blocks.

Consequently, with the exception of the old Medina, certain low-income areas, and some non-regulatory, spontaneous development areas, maximum permitted H/W ratios are low. In most of the city, zones B–D apply, and normal H/W ratios are therefore 0.3–1.2. Moreover, plot coverage is low, especially for detached slab blocks (zone C) and low-rise houses (zone D) where maximum plot coverage varies between 10 and 50%. If the wide roads are taken into account, the portion of the ground covered by buildings is even lower. Consequently, current urban codes prescribe a highly dispersed urban form.

Furthermore, the density of development, expressed as FAR, is low in Fez. Maximum FAR values in the new city vary between 0.2 for detached houses (villas) to about 2.7 for the densest city centre areas[3]. These low FAR values lead to low population density and highly inefficient land-use. Even the FAR values of the traditional buildings in the historic Medina are fairly low, at around 2.2, due to high ceilings and the limited number of storeys. The low FAR values of the formal areas stand in stark contrast to the high FAR values found in informal settlements.

In Fez, the urban codes for the modern part of the city prescribe an urban form that is the very opposite of that found in traditional architecture. While the contemporary urban form guarantees solar exposure of the street and façades, the traditional, residential areas of the Medina have narrow alleyways without setbacks and buildings often have projected upper floors and shading devices, resulting in almost complete shade at pedestrian level.

3 The figure is an estimation based on data from Table 2.2 (there is no FAR requirement for zone A).

Consequences for microclimate and outdoor thermal comfort

In Fez, the intention of the current urban codes is to guarantee daylight for buildings. This has resulted in a dispersed urban form with low to extremely low H/W ratios. This may be relevant for the winter period when solar elevations are low and passive heating of buildings is desired. However, during the long, warm summer, when there is a need for solar protection, the shade provided by buildings is extremely limited. Moreover, there are no requirements on shading of pedestrians with, for example, shading devices, colonnades, projecting upper floors or shade trees. For the warm season, this results in a very poor microclimate at street level, used by pedestrians conducting their daily activities. It also results in the warming of buildings and thus poor indoor climate or increased need for cooling. The worst conditions are found in areas designated for low-rise houses where plots are very large and plot coverage low. Apart from poor microclimatic conditions in the summer, land-use in these areas is highly inefficient, with a disproportionately large amount of ground occupied by streets, sidewalks and front yards.

The lack of climate concern can also be seen in the fact that basically the same regulation of urban form is exercised throughout the country despite extensive climatic variations. This is also true of the type of low-income housing used nationwide since 1964. This is currently under review (MHU 2005), with the preliminary result that roads 2 m narrower will be permitted, as well as the construction of up to five storeys (rather than three). However, these modifications, aimed at increasing the efficiency of land-use, are minor, and result in H/W ratios of 1.3–1.6. This is lower than current practice in Fez and will have negligible effects on the urban microclimate.

Urban codes in Colombo

Compared to the old code (Government of Sri Lanka 1980), which is still in force outside the Colombo Municipal Council and which prescribes a maximum H/W of 2.0, the current code allows slightly higher H/W ratios. Plot coverage prescriptions are almost identical; 65% for residential construction and 80% for non-residential, except for high-rise buildings, for which maximum plot coverage is restricted to 50%. A feature of the new code is also the prescription of side setbacks on middle and high-rise buildings, i.e. buildings of more than eight storeys.

H/W ratio, plot coverage and floor area ratio (FAR)

The regulations in force (UDA 1999b), which are described in Table 2.5, result in the H/W ratios shown in Fig. 6.24. This figure shows the H/W ratio for both the street canyon and the back yard, see Fig. 6.22.

It should be noted that the H/W ratios in Fig. 6.24 are based on an average storey height of 3.75 m. At a normal storey height of 3 m, including the floor structure[4], H/W ratios would be lower, since the maximum number of storeys must be respected. It should also be noted that it may be necessary for H/W ratios to be lower due to limitations of plot coverage and FAR. This is particularly likely for resi-

4 The minimum height, measured between the floor and the ceiling, is 2.8 m for living spaces and 3 m for ground floor shops (UDA 1999b).

Low-rise = Detached or terraced houses, max. 3 storeys

Intermediate-rise = Detached or attached blocks, max. 8 storeys

Middle-rise = Detached blocks, max. 12 storeys

High rise = Detached blocks, above 12 storeys

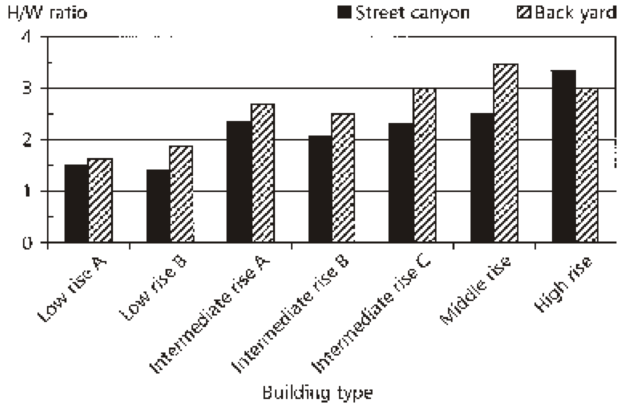


Fig. 6.24 The maximum H/W ratios of the street canyons and back yards permitted for different building types in Colombo. (Calculated from UDA (1999b). There is no maximum height limit for high-rise buildings. Here, the height has been assumed to be 60 m).

dential buildings, which have lower maximum plot coverage and FAR than commercial buildings.

Both the new and old codes place strict limits on projecting architectural details, such as shading devices on the street façade. Consequently, the shading of pedestrians on the street is not encouraged.

In addition to the stipulated street widths and setbacks, the authorities have often prescribed a so-called street line, or street reservation, indicating the future width of the road. No part of the building is allowed to project beyond this line. Therefore, the maximum allowed H/W ratios are likely to be considerably lower than the maximum values shown in Fig. 6.24.

As mentioned in Section 2.3, average FAR for existing buildings in Colombo is less than 1 (UDA 1999a). The new code proposes considerably higher maximum FAR values, varying from 1.5–2.25 for low-rise buildings, to as much as 8 for middle-rise buildings (and even higher for high-rise buildings). Consequently, the new codes allow for a considerable increase in population density.

Consequences for microclimate and outdoor thermal comfort

In Colombo, the intention of the current urban codes is to guarantee solar exposure of the buildings and ventilation around them. This has resulted in a dispersed urban form with low H/W ratios. Consequently, the shade provided by buildings is highly limited and results in very poor microclimate at street level where pedestrians conduct their daily activities. It also leads to the warming of buildings and thus poor indoor climate or increased need for cooling. Although slightly higher H/W ratios are permitted by the latest code (UDA 1999b), these are still too low to provide efficient shade. Moreover, there are no requirements for the shading of pedestrians with, for example, shading devices, colonnades or shade trees. On the contrary, the use of shading devices on façades is restricted.

On the other hand, maximum permitted plot coverage, 65% for residential buildings and 80% for non-residential, is quite high and for buildings up to 8 storeys there are no requirements for setbacks at the sides. Consequently, the construction of terraced houses and attached residential blocks is encouraged, decreasing the ventilation around the buildings.

The consideration of climate aspects in urban planning and design

The aim of the interviews was to ascertain the extent to which climate is considered in urban planning and design, what are the constraints preventing the consideration of climate issues, what is the role of the urban codes, and in what way could climate aspects be included in the planning and design processes? The findings have been grouped according to these questions.

Interviews in Fez

Consideration of climate issues

According to the interviewees, climate issues are not explicitly considered in urban planning and design. There are very few projects where architects have considered climate aspects in the design of buildings or urban neighbourhoods. On the other hand, environmental issues are being ascribed an increasingly high priority.

Reasons why climate is not considered

One reason why climate is not considered, mentioned by several respondents, was that much of today's construction consists of low-income housing. A major problem in these areas has been high population density and many town planners are concerned about hygiene conditions. Therefore, in order to prevent the health problems caused by overcrowding, low-density settlements with wide roads are being built. Many interviewees also pointed out that in low income areas, the main aim is to keep costs at a minimum. Consequently, it is very difficult to introduce any measures that would increase costs, such as improving comfort conditions.

Another obstacle mentioned by a few respondents was that various security regulations must be adhered to. For example, the fire brigade requires sufficiently broad streets and space is also needed for infrastructure services such as sewerage and electricity.

One informant mentioned the problem of conflicting interests where the client and architect are often more concerned with the individual building than with urban design. He also claimed that there has been a trend in recent decades to build isolated, spectacular buildings rather than considering uniform urban design.

The interviews gave no evidence of any explicit interest in, or demand for, climate-conscious urban design. None of the informants had any specific education in climate-conscious urban design and the access to tools is likely to be limited.

The role of urban codes

The general opinion of the planners interviewed was that current regulations are suitable and well-founded, including the Casablanca by-law from 1952, which provided the basis for urban codes in other cities. The urban regulations in Fez are normally followed strictly. However, a few informants claimed that this is not always the case; non-regulatory developments exist in low-income areas, as well as in medium and high-income neighbourhoods. In low-income areas, illegal storey additions and building extensions into courtyards are common. In medium and high-income areas, exceptions from the urban codes are possible, especially if the architect and urban designer are able to argue for another urban design.

Several respondents did not view the current urban codes as an obstacle for climate-conscious urban design or “bioclimatic” architecture. One respondent argued that although he did not see the current code as an obstacle, he had to admit that the current codes did not, on the other hand, favour climate-conscious urban design. For example, dense “medina type” developments are not possible. A few informants pointed out that current codes were imported from France and are not really suited to the Moroccan context.

Ways to include climate issues

Several informants argued that better knowledge on climate aspects is needed among urban designers and planners. One respondent claimed that current codes and regulations would not hinder knowledgeable designers from achieving a favourable urban environment. Furthermore, he argued that the role of the authorities is to interpret the text of the codes in relation to each situation. Thus, he continued, the urban designer (or developer) is able to achieve an individually unique neighbourhood if he can convince the authorities. Another interviewee claimed that the authorities can establish special codes for individual housing areas.

One informant argued that more research is needed about climate-conscious planning and design.

Interviews in Colombo

Consideration of climate issues

A majority of the informants claimed that they considered climate issues in urban planning and design. Although the extent to which climate was considered varied between the respondents, the general impression was that climate issues are not thoroughly studied and have low priority.

At the comprehensive planning level, for example when choosing the site, climate data, such as temperature and rainfall are often gathered. However, several respondents pointed out that this data is not analyzed and the link to design is missing. At the detailed planning level, a few interviewees said they considered the microclimate around the buildings whereas some thought climate issues were considered by applying the urban codes, which “give priority to light and ventilation”. Several respondents said climate issues were considered unintentionally or “in the back of our heads” deriving from extensive experience of living in the climate and knowledge of traditional solutions. The most common level where climate issues are considered seems to be architectural design.

Many of the informants recognised that high temperatures affect people's working efficiency and that thermal comfort is important for good performance.

Most of the respondents also expressed a personal interest in climate and thermal comfort issues. This interest was especially great among urban planners, urban designers and architects but was weaker among builders and developers.

Reasons why climate is not considered

Several reasons were identified as to why climate issues are considered only to a very limited extent in urban planning and design. Many respondents pointed out the lack of knowledge and training, both among professionals and the public. One respondent said that there is a lack of skilled people and that the practice is lacking. Most informants also pointed out the lack of tools and lack of access to existing tools as a barrier.

Most informants have no education whatsoever in urban climate and outdoor thermal comfort. A few informants, though, had a degree in urban design, or the like, from abroad. Educational programmes also covered climate issues, albeit only for temperate climates. Respondents with an architectural background had, however, a general education in climatic building design and indoor thermal comfort.

The utilisation of tools for climate-conscious planning and design appears to be very limited. One respondent mentioned climate atlases that show, for example, rainfall, and maps of disaster-prone areas. A few respondents said they used climate data such as temperature, humidity and rain. No respondent had used, or even heard of, specific tools for climate-conscious urban design, such as climate maps, graphic or computer-based tools for the calculation of shade, radiant temperature, etc.

In general, there seems to be a lack of information, both regarding climatic data and guidelines. Many said that they had no access to data and one respondent pointed out that climate data should not only be accessible, but must be analysed and interpreted in order that it be possible to understand how to use it. One respondent indicated that it takes too much time to gather the necessary information, review it and make assumptions. Moreover, he continued, it is difficult to know what information to look for when you are not familiar with the field. Another interviewee pointed out that there is a lack of knowledge on how to interpret available data.

A major barrier involves conflicting interests and other priorities in the planning and design process. A few informants pointed out that thermal comfort is subjective and difficult to measure. Consequently, other problems, which are considered more important or urgent, are likely to be assigned priority. Several interviewees said that the main problems in urban planning include sanitation, environmental issues, such as solid waste and wastewater disposal, and infrastructure. Other informants mentioned environmental problems, such as air pollution and dust, which are direct health problems, and the protection of wetlands and bodies of water.

The role of the urban codes

According to the informants, the urban and building regulations are normally followed strictly. One important reason for this is that unless the building conforms to the regulations, the owner will not receive the certificate required for infrastructure connections. However, several informants said that extensions are commonly built after the certificate has been received. One informant pointed out that exceptions from the rules can occur in larger projects involving influential architects and clients.

The opinion of the majority of the informants was that the recently revised urban and building regulations are good. One informant thought it was good that side setbacks and lower plot coverage had been introduced for middle and high-rise buildings. However, there was also some criticism. One informant indicated the lack of prescriptive guidelines for shading, while another felt the codes constituted an obstacle due to their lack of flexibility. Another criticism was that the codes did not prescribe trees along roadsides.

Ways to include climate issues

All informants had ideas on how to include climate issues in planning and urban design. The suggestions concerned the planning process, the role of urban codes and guidelines and education.

One informant said that it should be possible to include climate issues in the planning process without difficulty, because there is an interest – it is just a matter of "expanding the scope". Regarding which planning levels should include climate aspects, opinion was inconsistent. Most informants, however, suggested that issues of climate and thermal comfort should be included at all levels of planning and design, from comprehensive to detailed level.

A majority of the informants expressed the view that the most efficient way to involve climate issues would be to include them in zoning, planning and building regulations. The main reason stated was that the codes are generally respected and that the consideration of climate aspects will therefore become praxis. One informant pointed out that if requirements are built into the planning regulations, people will begin to consider these issues already at the building permit stage. Many also suggested developing planning and design guidelines.

The suggested content of codes or guidelines included prescriptive guidelines on the minimum percentage of green areas, green belts and bodies of water, the minimum amount of open space, requirements on shade trees, increased minimum plot sizes (to allow for more ventilation) and requirements on the reflectivity of paving materials (to avoid heat absorption).

A general opinion was that education is important in increasing knowledge among professionals in the field. One informant suggested that climate issues should be included in the university education of urban planners. One informant said, on the other hand, that education should be provided, not only via universities, but also at other organisations involved in planning, urban design and housing.

He added that a stronger link between the universities and public institutions is necessary to enable the exchange of information and knowledge. One informant stressed the importance of generating awareness, both among professionals and the public, for example through newspaper articles.

Several respondents also pointed out that public demand for climate-conscious design may develop, at least among the middle and high-income population. One respondent argued that rising living standards will create a demand in the future - there is already a demand for a better environment. Some respondents, however, did not feel there was any demand, particularly from low-income residents who have other priorities and are not aware of the problem or of the possible benefits of climate-conscious design.

7 Discussion and conclusions

This chapter discusses the results of the previous chapter and their implications for climate-conscious urban design in hot climates, exemplified by the cities of Fez and Colombo. The first section deals with the influence of different design parameters on the microclimate and outdoor thermal comfort. In the second section, the consideration of climate aspects in urban planning and design is discussed. The third section contains conclusions regarding how to design urban areas to achieve outdoor thermal comfort. The final section contains suggestions for future studies.

7.1 Influence of urban design on outdoor thermal comfort

Urban-rural differences

In both Fez and Colombo, urban-rural temperature differences were found to be significant, both by day and by night. Whereas the urban canyons studied in both cities were warmer than the rural sites by night, some sites were warmer and others cooler by day. The urban-rural temperature differences are linked to urban geometry, which indicates the importance of urban design in providing comfortable urban environments.

By day, the sites with shallower street canyons were, in general, warmer than the rural sites due to their high absorption of solar radiation. Deeper canyons, however, tended to be cooler than the rural sites due to the protection they afforded against solar radiation. In the case of Colombo, the reason for the cool islands is likely to be a combination of shade from buildings and cooling by the sea breeze. Similar urban-rural daytime differences have been observed by e.g. Bourbia and Awbi (2004) in a hot dry climate and by e.g. Nichol (1996) and Jonsson (2005) in hot humid climates.

In Fez, the "deep" canyon (SEF) had the strongest nocturnal heat island. This was to be expected given the far greater height-to-width (H/W) ratio (lower sky view factor) than in the "shallow" canyon (ADA). The observed seasonal variation, with stronger heat islands in the summer than in the winter, agrees well with studies conducted in mid-latitude cities (Arnfield 2003). This is probably because the higher amount of rainfall in the winter period leads to higher soil moisture at the rural site, as well as more clouds and consequently higher sky emissivity (see e.g. Oke et al. 1991).

The nocturnal heat island found in Colombo is weaker than those commonly observed in temperate climates. This is most probably linked to the high amount of rainfall, resulting in high soil moisture levels at the rural site, as well as the high humidity in the air and high degree of cloud development, causing high sky emissivity (see e.g. Oke et al. 1991). The results agree well with those from other hot-humid coastal cities, such as Singapore (2°N) (Tso 1996) and Dar es Salaam (7°S) (Jonsson 2005).

Microclimate and outdoor thermal comfort in Fez

Effect of H/W ratio

In Fez, it was shown that the H/W ratio influenced all of the environmental parameters measured, particularly air temperature and MRT.

The fact that the maximum air temperature was found to decrease with increasing H/W ratio agrees with other studies in similar climates (Coronel and Alvarez 2001, Bourbia and Awbi 2004 and Ali-Toudert et al. 2005). However, none of these studies examined canyons as deep as those included in this study and they did not find intra-urban differences as large as those found here, where the deep canyon (H/W ≈ 10) in the compact neighbourhood (site SEF) was up to 10°C cooler than the shallow canyon (H/W ≈ 0.6) in the dispersed neighbourhood (site ADA) on the warmest summer days.

The reason for the large daytime cool island in the deep canyon is its high H/W ratio. By day, the lower part of the canyon is in complete shade and, consequently, the air is not warmed. Moreover, in contrast with the shallow canyon, which is penetrated by the air from above, the deep canyon is, to a large extent, isolated from the warm air above that skims over it (Fig. 3.4). The reason for the intra-urban differences being smaller during the winter is probably the fact that diurnal temperature swings are smaller in the winter due to less intensive solar radiation, because of lower solar altitudes, and because of the greater amount of overcast and rainy weather.

The simulated maximum daytime air temperatures (Fig. 6.11) agree well with the results of the field measurements in the shallow and deep canyons in Fez, especially in the summer (Figs. 6.1a and 6.2). The simulations indicated that the cooling effect on the air temperature tended to be especially big for canyons with H/W ratios of around 2 and above in summer and for H/W = 1 and above in winter.

The parameter that was most affected by the H/W ratio, apart from the air temperature, was MRT at pedestrian level. The canyon geometry influences both the exposure to solar radiation and pedestrians' radiative heat exchange, as well as surface temperatures. The difference in surface temperatures between the deep and shallow canyons in Fez proved to be huge, both during summer and winter. The pattern agrees well with differences between deep and shallow canyons found by Ali-Toudert et al. (2005) in hot dry Beni-Isguen (32°N), although their study included only summer conditions.

The higher vapour pressure in the deep canyon compared with the shallow one is probably attributable to moisture in the deep canyon not being dispersed through ventilation, due to the stable conditions there. In the shallow canyon, on the other hand, good ventilation is provided by the wind that enters and natural convection is high (see e.g. Mayer et al. 2003). It should be noted that, throughout the year, vapour pressure in both of the canyons studied in Fez is well below the critical level of approximately 25 hPa suggested by Givoni (1998), see Section 3.2. Consequently, humidity is not likely to significantly affect thermal sensation.

The tendency for daytime PET, based on measurements, to decrease with increasing H/W ratio was observed for both the summer and winter seasons. The summer results agree well with the findings of Ali-Toudert et al. (2005) in Beni-Isguen, Algeria. However, in general, their field study evidenced less intra-urban variation and higher PET values than were observed in the summer in Fez. This is explained by lower variation in H/W ratio and higher air temperatures in their case.

Thermal comfort, based on measurements, showed extensive differences in PET variation between the deep and the shallow canyons, both in summer and winter. It should be noted that, in reality, a person in the shallow canyon has the option of moving between sunny and shady locations. However, this is only really possible during the cold season. In the summer, when the solar elevation is high, it is almost impossible to find shade, partly because pavements are situated 4 m from the façades because of setback regulations. In the winter season, discomfort in the deep canyon could, to some extent, be compensated for by heavier clothing, although the total lack of solar access at pedestrian level contributes to discomfort.

The magnitudes of the simulated PET values (Figs. 6.12 and 6.13) agree fairly well with the measurement-based results (Fig. 6.8). The simulations, in which a greater variety of H/W ratios were studied than in the measurements, confirmed the trend for PET to decrease with increasing H/W ratio, both in summer and winter. The summer results agree well with the findings of Ali-Toudert and Mayer (2006) in a similar climate.

Effect of street orientation

Whereas other field studies have found north-south streets to be significantly cooler than east-west streets, e.g. Bourbia and Awbi (2004) and Pearlmutter et al. (1999), street orientation was found to have an insignificant impact on air temperature. This is due to the fact that predominantly deep and shallow canyons were studied in Fez. In the compact neighbourhood, alleys are so narrow and winding that solar radiation seldom penetrates, irrespective of street orientation. In the dispersed neighbourhood, on the other hand, the streets are so wide that temperature differences between them will probably be levelled out by horizontal air movements (micro-advection, see e.g. Eliasson 1996).

The simulated effect of orientation on air temperature was found to be fairly small, less than 2°C for the summer and less than 1°C for the winter (Fig. 6.11), and negligible for H/W ratios above 2. The fact that north-south oriented streets were cooler than the east-west oriented streets in the summer agrees well with the simulations by Ali-Toudert and Mayer (2006) for a similar climate, although they found a maximum difference for H/W = 2. In this study, in contrast with the summer case, north-south streets were found to be slightly warmer than east-west streets. However, in reality, the difference in air temperature will be less because of the influence of street intersections and the mixing of air between streets of different orientation as discussed above.

Even if the effect of street orientation on air temperature may be limited, the effect on MRT tended to be significant, as reflected by the PET index. The fact that north-south oriented streets give lower PET than east-west oriented streets of the same H/W ratio agrees well with the findings of Ali-Toudert and Mayer (2006). Similarly, Pearlmutter et al. (2005) found the radiative heat gain of a body in the centre of the canyon to be lower in north-south streets than in east-west streets. The difference in PET is most pronounced for H/W ratios of less than about 4, since for higher H/W ratios, the amount of solar radiation reaching the street is small, regardless of orientation.

Effect of shading by colonnades and trees

The simulations showed that shading by colonnades and trees was very efficient in lowering PET. This trend agrees well with the findings of Ali-Toudert and Mayer (2005, 2006). Shading is especially efficient in the summer climate of Fez, since solar radiation is dominated by the direct component. As expected, colonnades are more efficient than shading trees, since the latter have some transparency.

Effect of surface reflectivity and thermal mass

The simulated effect of the reflectivity and thermal mass of surfaces proved to be surprisingly small. This is not in agreement with several guidelines proposing light surface colours to keep surface temperatures low during the warm season (see Section 4.4). Even though highly reflective materials are likely to have a positive effect on thermal comfort, it can be difficult to maintain light colours due to dust in hot dry climates and colours that are too bright may cause problems of glare.

It should be noted that the effect of both the surface reflectivity and thermal properties of surface materials might have been more significant if a simulation programme had been used that took the thermal mass of buildings into account. However, no such programme is available that also is user-friendly.

Microclimate and outdoor thermal comfort in Colombo

Effect of H/W ratio

As in the case of Fez, it was shown that the H/W ratio influenced all of the environmental parameters measured. The measurements in Colombo evidenced the significant impact of urban geometry on daytime air temperatures. The fact that the maximum daytime temperature tended to decrease with increasing H/W ratio was also found by Ahmed (1994) in the hot humid summer in Dhaka (24°N). This tendency has also been found in many hot dry climates, such as in the case of Fez discussed above.

The negligible differences in air temperature between canyons of different H/W ratios found in the Colombo simulations are likely to be linked to the simulation programme, see Section 5.2 and Paper IV.

As in the case of Fez, the H/W ratio had a great effect on surface temperatures and on MRT at pedestrian level. Canyon geometry influences both exposure to solar radiation and pedestrians' radiative heat exchange, as well as surface temperatures. The huge difference in surface temperatures between sunlit and shaded areas agrees well with the findings of Nichol (1996) in Singapore.

The reason why no link could be found between urban geometry and the level of humidity, as was the case of Fez, is probably that the H/W ratios between the Colombo canyons vary less. Other factors also have a significant impact, such as the amount of vegetation, the permeability of the ground and the proximity to the sea. Although the average vapour pressure for the urban sites was lower than that of the rural station by day, it by far exceeded the critical level of approximately 25 hPa suggested by Givoni (1998), see Section 3.2. Humidity is thus likely to have a significant negative impact on thermal comfort, since the evaporative cooling potential of the human body decreases at such high levels of humidity.

The measurement-based PET calculations show the importance of shading by buildings for the improvement of daytime thermal comfort. Higher H/W ratios can, thus, provide more comfortable conditions than low H/W ratios. For the canyons with higher H/W ratios, such as the Pettah (DMP) and Bank of Ceylon (BoC) sites, shade was available in the early morning and late afternoon. However, the highest H/W ratio was only 1.2 (at the DMP site) and, in all of the canyons investigated, the possibility of finding shade from buildings was limited on both sides of the street, particularly between about 11:00 h and 15:00 h when the solar elevation is high. For some streets, the period with no possibilities for shade was even longer, since pavements are located some meters from the façades due to setback regulations.

The simulated PET values (Fig. 6.15) agree fairly well with the measurement-based results for a "clear" day (Fig. 6.9) and confirm the relationship with canyon geometry. From the simulations, which considered a greater variation in canyon geometry than the measurements, there was a clear trend for decreasing PET with increasing H/W ratio. The results agree well with some studies in hot dry climates, as discussed above for the case of Fez.

Effect of street orientation

The simulated effect of street orientation on PET was significant, showing that both maximum PET and the duration of uncomfortably high PET values are lower for north-south oriented streets. For such streets, shade is provided by the buildings both in the morning and the afternoon provided the H/W ratio is sufficiently high. East-west oriented streets are far more problematic. However, there will be shade on the south side of the street during the period October–March provided buildings on this side of the street are sufficiently tall. During the remainder of the year, the sun is at its zenith, or slightly to the north, making it difficult to achieve shade without some kind of overhead shading.

Effect of the sea breeze

The measurements showed clear evidence that the sea breeze has a positive effect, due to its lower air temperature and higher wind speeds, which have a cooling effect during in the afternoon. This is clearly illustrated by the difference between the Bank of Ceylon (BoC) site in Fort and the Galle Road (GRB) site in Bambalapitiya. Although both are close to the sea, the former, which is open to the sea, is more comfortable due to the sea breeze, whereas the latter has a continuous frontage of medium-rise buildings along its western side effectively blocking the sea breeze.

The findings agree well with those of Jonsson (2005) in hot humid Dar es Salaam, Tanzania, where the sea breeze was found to create a daytime cool island during the inter-monsoon period. The effect of sea breeze on urban climate was also noted by Saaroni et al. (2000) in Tel-Aviv, Israel, where areas close to the sea, or where the sea breeze was allowed to penetrate by the urban morphology, were cooler than other parts of the city.

Effect of shading by colonnades and trees

Overhead shading can improve comfort conditions considerably, as is clearly illustrated by the calculated PET for the street at the University of Moratuwa (UoM) site, where overhead shading existed on one side of the street. The simulations also show that shade from either colonnades or trees gives considerably lower PET values, resulting in comfortable or only slightly uncomfortable conditions according to the assumed comfort limits. These findings agree with Ahmed (2003), who found that well shaded urban spaces often were considered comfortable in the hot humid summer climate of Dhaka, Bangladesh. As noted in the Fez case, colonnades provide more efficient shading than trees, since the latter have a certain degree of transparency.

Simulated PET values under colonnades and trees are slightly higher in the Colombo case than in the Fez summer case, although global radiation in Colombo is lower (see Paper IV). This is due to the higher amount of diffuse radiation in Colombo.

Effect of surface reflectivity and thermal mass

The simulated effect of the reflectivity and thermal mass of surfaces proved to have a limited influence on thermal comfort. However, even if lighter colours could improve comfort conditions, as suggested by many guidelines, maintaining light colours could prove difficult, due to dust and air pollution. Although there is a slight tendency for PET to decrease with increasing thermal admittance, it is not realistic to introduce heavier building materials, since those that exist are already of medium to high density.

As noted for the Fez case, the effects of both surface reflectivity and thermal properties might have been more significant if a simulation programme had been used that takes the thermal mass of buildings into account.

7.2 The consideration of climate in urban planning and design

The role of urban codes

Urban codes have a major impact on urban design in both Fez and Colombo, since they include strict regulations on building heights, street widths, plot coverage, etc. The codes are respected and tend to be followed strictly in formal construction in both cities. However, in Fez, and Morocco in general, urban codes are largely inappropriate from a climate point of view. Instead of promoting shade, which is crucial in warm climates with intense solar radiation, the codes stipulate large distances between buildings. Similarly "inappropriate" codes have been reported from other warm climates (e.g. Al-Hemaidi 2001, Baker 2002).

However, due to rapid urbanisation in both Morocco and Sri Lanka, there is an ongoing debate regarding approaches to increasing the population density through the revision of the urban codes. Hence, the latest code for Colombo (UDA 1999a, b) promotes high-rise buildings and allows maximum floor area ratio (FAR) values of 8 and above. In Morocco, low-income dwellings will be permitted to have more storeys (MHU 2005). However, although the ongoing changes are in the right direction in both countries, they will not improve outdoor thermal comfort conditions significantly as they will only result in minor increases in maximum H/W ratios.

Consideration of climate aspects in urban design

The interviews with urban planners conducted in this study revealed that the consideration of climate in urban planning and design is limited both in Fez and Colombo. Climate is not considered explicitly but is, instead, included in other aspects, such as environmental issues. Eliasson (2000) came to a similar conclusion after interviewing Swedish urban planners.

Constraints for climate-conscious urban design

There are a number of constraints explaining why climate issues are not considered in urban design. One important constraint is the lack of knowledge about climate issues among urban planners and designers. Apart from limiting opportunities for climate-conscious urban design, this lack of knowledge is likely to make it more difficult for urban planners to argue for climate aspects when conflicts of interest occur, as suggested by Eliasson (2000). There was no evidence that consultant expertise, such as that offered by meteorologists or climatologists, was used. Another major problem is the lack of user-friendly tools to predict the effect of urban design on the microclimate. The use of tools was limited to climate data from climate

Atlases. The findings of this study agree quite well with those of Eliasson (2000), except that the Swedish planners had access to somewhat more tools and occasionally employed the services of climate consultants.

Ways to incorporate climate issues in urban design

Several respondents suggested ways to better incorporate climate issues in the urban planning and design processes. A common proposal was to include climate aspects in zoning and building regulations. This approach is supported by Aynsley and Gulson (1999), who argue that climate aspects should be a legislated planning requirement. There were also suggestions for the development of planning and design guidelines. The latter suggestion agrees with the conclusions of Evans and de Schiller (1996) in Argentina.

Undoubtedly, urban codes play an important role in the provision of climate-conscious urban design. However, governing climate-sensitive urban design solely through codes only is not feasible. For example, a variety of different street designs may be needed to provide comfort. Consequently, it is necessary for planners and urban designers to be knowledgeable about urban climate while also cooperating with climatologists. The interviewees were also of the opinion that education is important, especially for professionals within the fields of urban planning and design. Moreover, public awareness was considered important.

7.3 How to improve thermal comfort at street level

Presented below are proposals for climate-conscious street designs for Fez and Colombo. These are mainly based on the simulation study, but also take measurement results and current urban design practices into account. It should be noted that no comfort zone for PET in hot dry and hot humid climates has been established. The discomfort limits assumed in this study are therefore uncertain. This particularly concerns the lower discomfort level in Fez during the winter, which is based on indoor clothing and activity and which, in reality, is therefore likely to be lower than that shown here.

Recommendations for hot dry climates

The studied city of Fez is used here to represent a hot dry climate. With the exception of its ancient Medina, Fez is, in general, a dispersed, low-rise city. The simulations showed that canyons with high H/W ratios, where buildings provide shade, represent an advantage under summer conditions. On the other hand, for the winter season, a dispersed urban form, with streets with low H/W ratios, is preferable. However, since the summer season is longer than the winter season and since it is more difficult to adapt behaviour and clothing to warm conditions, the majority of streets should be designed for good summer comfort. This would require new urban areas being far more compact than today's to improve microclimatic conditions during the warm season.

Higher H/W ratios could be achieved either by making the streets narrower, which could be suitable for pedestrian streets, or by making the buildings higher, which is more suitable for streets intended for motor traffic. However, an increase in H/W will lead to higher nocturnal temperatures, which may decrease the possibility of cooling by night ventilation. Moreover, as streets become narrower, problems of privacy increase, with neighbours being able to see into dwellings from across the street. Furthermore, very deep canyons would be unfavourable from the perspective of the dispersion of pollution from motor traffic. Therefore, extremely deep canyons are not recommended.

The simulation study suggested that H/W ratios for east-west oriented streets should be as high as 4 to provide comfort in the summer (Fig. 6.17b). For north-south oriented streets, which turned out to be less problematic in terms of thermal comfort, a H/W ratio of about 2 provided acceptable conditions both in summer and winter (Figs. 6.17a and 6.18a). To provide thermal comfort on a neighbourhood level also in winter, at least some streets, preferably oriented east-west, should be wider to allow for solar access. The canyon of H/W = 0.67 with a colonnade on its northern side and trees planted along the southern side (Fig. 6.18b) provided sufficient solar access under the colonnade in winter, while providing sufficient shade under the same colonnade and under the shading trees on the southern side in summer. The proposed H/W ratio of 4 for east-west oriented streets is higher than that proposed by e.g. Givoni (1998) and Grundström et al. (2003). However, the suggested canyon of H/W = 0.67, intended to permit solar access, is in line with the proposals of these studies. The H/W ratio of 2 that this study proposes for north-south oriented streets is lower than that proposed by Givoni (1998), who suggested H/W ratios between 3 and 5.

It is recommended that buildings have no front setbacks, in order to increase the possibilities of shade for pedestrians. Moreover, overhead shading should be provided in the form of projected upper floors, colonnades, shading trees or other devices to improve thermal comfort for pedestrians. Deciduous trees are suitable since they provide shade in summer and allow solar access in winter.

Open public spaces should preferably be small, but sufficiently large to allow solar access in winter. They should be provided with overhead shading to improve comfort in summer.

Most of the proposed street designs are not possible to achieve given current urban regulations in Fez, particularly not in low-rise residential areas where plots are often large with required setbacks. Consequently, it would be necessary to change the codes to permit higher H/W ratios for streets than is currently the case. Moreover, plot coverage should be increased and there should be no front setbacks. There should be fewer zones for detached villas and plots should be smaller. Such a shift, to a more compact urban design, would lead to higher building and population densities and thus a more efficient land-use, which is in line with the aims of the national authorities. The codes should also promote projecting upper floors and colonnades, which provide shade at street level. Similarly, horizontal shading devices and shading trees should be encouraged.

Recommendations for hot humid climates

The studied city of Colombo, which is used here to represent a hot humid climate, is, in general, a dispersed, low-rise city. The simulations showed that canyons with high H/W ratios, where shade is provided by buildings, would be desirable to improve microclimatic conditions. This could be achieved either by making the streets narrower, which could be suitable for pedestrian streets, or by making the buildings higher, which is more suitable for streets intended for motor traffic. However, excessively high H/W ratios are likely to increase the nocturnal heat island, which would be negative in Colombo where nocturnal temperatures are high. Moreover, this would restrict air flow and would be unfavourable from the perspective of the dispersion of pollution from motor traffic. Therefore, extremely deep canyons are not recommended.

The simulation study suggests that H/W ratios for east-west streets should be as high as 4 to provide comfort in the summer (Fig. 6.20a). For north-south streets, which proved less problematic in terms of thermal comfort, a H/W ratio of about 2 provides acceptable conditions (Fig. 6.19). In Colombo, spacing between buildings is preferable to permit air flow. This is especially important for the coastal strip to allow the westerly sea breeze to penetrate the city. Consequently, some east-west oriented streets in coastal areas could have H/W ratios as low as about 0.5 (Fig. 6.20b). The H/W ratios proposed in this study are considerably higher than those normally suggested for hot humid climates (see Section 4.4).

Detached tower blocks are well adapted to the hot, humid climate, since they provide a large amount of shade while allowing the wind through and, in fact, stimulating air flow. A blend of high-rise towers and lower buildings, as suggested by de Schiller and Evans (1998) and Aynsley and Gulson (1999), and the use of buildings raised on columns would probably promote even greater air flow. It should be noted, however, that wind speeds in Colombo are, in general, low and the possibilities are therefore limited. However, the possibilities of enhancing air flow require further investigation, as suggested in Section 7.4.

It is recommended that buildings have no front setbacks, in order to increase opportunities to provide shade for pedestrians at street level. However, side setbacks are recommended to increase air movements around buildings and in the streets. Moreover, overhead shading should be provided in the form of projected upper floors, colonnades, shading trees or other devices to improve thermal comfort for pedestrians. Similarly, open public spaces should be provided with overhead shading to improve comfort.

H/W ratios above about 2, as suggested above, are currently not permitted in Colombo and, consequently, urban codes need to be changed. Such a change would lead to higher building and population densities, which is in line with the aims of the national authorities. Instead of front setbacks, codes should stipulate side setbacks to increase air flow. Projecting upper floors and colonnades, which provide shade at street level, should be promoted and horizontal shading devices and shading trees should be encouraged.

7.4 Future studies

In this study, thermal comfort was calculated theoretically and comfort limits were estimated on the basis of other studies. Moreover, the effects of climate adaptation were not considered. Therefore, there is a great need to conduct field surveys in hot dry and hot humid climates in order to determine actual comfort zones. Such field surveys should include simultaneous microclimate measurements at street level and subjective comfort votes by pedestrians.

Detailed, climate-conscious urban design guidelines and regulations need to be developed for Fez and Colombo. These should include requirements and recommendations regarding street widths, building heights, the spacing of buildings, street orientation, desirable building forms, plot coverage, shading devices, shading trees, surface materials and façade colours. However, since this study was restricted to east-west and north-south oriented streets, the performance of other street orientations needs to be investigated for the two cities.

This study showed the importance of overhead shading in warm climates. Future studies should include *in situ* measurements to develop more detailed knowledge on the effect of shading devices and shading trees.

Wind speeds need to be promoted in hot humid climates, especially where wind speeds are low. The design of urban areas to promote air flow needs to be studied thoroughly, for example by using detailed CFD modelling.

In future studies, it would be interesting to investigate the effect of urban design on thermal comfort and energy use in buildings. Such studies should include the link between architectural and urban design.

Due to the complexity of the urban environment, simulation models are important in understanding how it affects urban climate and to predict the effects of different urban designs. While highly comprehensive and providing detailed output, the simulation programme used in this study, ENVI-met, does not consider the thermal mass of buildings. Future microclimate simulations should preferably use models that take this parameter into account.

In order to increase opportunities for urban designers to *design* comfortable outdoor environments, there is a need to develop user-friendly design tools. Such development should preferably be conducted in cooperation between urban climatologists and urban designers.

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Glossary of terms and definitions

Advection	Horizontal air movements
Albedo	Reflectivity
Anthropogenic heat	Heat release from human activities.
Atmospheric stability	The atmosphere is said to be *unstable* when the air temperature decreases with height (typical for sunny days when solar radiation induces natural convection), *stable* when the air temperature increases with height (typical for calm nights) and *neutral* when there is no temperature gradient.
Density (building)	Amount of the ground occupied by buildings.
Density (residential)	No. of persons per unit of land (or no. of housing units per unit of land).
Dry bulb temperature	The air temperature of a dry thermometer.
Emmisivity	The ratio of energy emitted from a surface compared to a black body.
Evapotranspiration	Loss of water to the air due to combined evaporation and transpiration.
Floor area ratio (FAR)	The ratio between the total gross area of a all floors of a building and the plot area
Forced convection	Air motion caused by wind.
Global radiation	The sum of direct and diffuse solar radiation.
Globe thermometer	A thermometer enclosed in a black painted globe used to measure the mean radiant temperature.
Impervious surface	A surface through which water cannot penetrate.
Land-use	The activity land is used for.
Latent heat	The heat required to change the state of water, e.g. from liquid to vapour, without change of temperature.
Long-wave radiation	“Low temperature” radiation, e.g. heat radiation from building surfaces.

Master plan	Document describing, in words and with maps, an overall development concept including both present land-uses as well as future land development.
Mean radiant temperature (MRT)	The temperature of an imaginary enclosure with which the human body would exchange the same radiation as with the actual environment.
Medina	Here used in the context "old", historic city.
Natural (free) convection	Vertical air motion due to density differences.
Octa	Unit that expresses the portion of the sky covered with clouds (equal to one-eighth of the sky vault).
Physiologically equivalent temperature	The air temperature in a typical indoor setting at which the heat balance of the human body is maintained with core and skin temperatures equal to those of the actual environment
Plot coverage	The amount of a plot covered by buildings.
Sensible heat	Heat energy that can be sensed, i.e. measured by a thermometer.
Setback	A required distance from the plot border to the building occupying the plot.
Shanty town	Informal settlement with "non-permanent" buildings, often lacking land ownership.
Short-wave radiation	"High temperature" radiation emitted by the sun.
Sky view factor (SVF)	The portion of the sky that can be seen from a point on a surface.
Slum area	Area of permanent buildings in very poor condition and lacking basic sanitary facilities.
Solar altitude	The vertical angle between the sun's position and the horizon.
Solar azimuth	The horizontal angle of the sun in relation to north.
Spontaneous settlement	Unplanned, non-regularized, and often illegal, human settlement.
Thermal admittance	The ability of a surface to take up or release heat (also called the heat penetration coefficient).
Turbulence	A state of the air in which air speed and direction vary randomly.

Urban canopy layer	The atmospheric layer between the ground and the roof tops
Urban street canyon	The space delimited by the street and the façades of the buildings along the street
Urban design	Part of urban planning that focuses on the design of places, i.e. buildings and the three-dimensional space between them. It is often defined as an intermediate scale between architecture and urban planning.
Urban fabric	The physical structure of an urban area.
Urban form	The physical form of an urban area consisting of street patterns, building sizes and shapes, architecture, and density.
Urban growth	The increase in urban population.
Urbanization	The growth of the proportion of urban population in a country.
Urban heat island	Urban areas being warmer than the surrounding rural areas. Primarily a nocturnal phenomenon.
Urban sprawl	Horizontal growth of a city through low-density developments.
U-value	The amount of heat per unit area that passes through a building element.
Vapour pressure	The partial pressure of the air due to water vapour.
Wilaya	Here: administrative region (Morocco).

Appendix 2

Material properties

Table A 1 Short-wave reflectivity (albedo) and long-wave emissivity (and absorptivity) of typical rural and urban surface materials (Evans 1980, Oke 1987).

Surface	*Short-wave reflectivity α*	*Long-wave emissivity ε and absorptivity*
Dark, wet soil	0.05	0.98
Light, dry soil	0.40	0.90
Long grass	0.16	0.90
Short grass	0.26	0.95
Asphalt	0.05–0.20	0.95
Concrete	0.10–0.35	0.90
Brick	0.20–0.40	0.90–0.92
White paint	0.50–0.90	0.85–0.95
Red, brown and green paint	0.20–0.35	0.85–0.95

Table A 2 Typical values of volumetric heat capacity, thermal conductivity and thermal admittance of typical rural and urban materials.

Material	*Heat capacity ($kJ/m^{3}°C$)*	*Thermal conductivity (W/m°C)*	*Thermal admittance* ($J/m^{2}s^{0.5}°C$)*
Sandy soil, dry	1300	0.30	600
Sandy soil, saturated	3000	2.2	2600
Clay soil, dry	1400	0.25	600
Clay soil, saturated	3100	1.6	2200
Asphalt	1900	0.80	1200
Brick	1400	0.70	1100
Concrete	2100	1.5	1800
Natural stone	2300	2	2100
Softwood	1400	0.14	400

* *Sometimes called heat penetration coefficient or thermal effusivity.*

Sources: Evans 1980, Oke 1987, Oke 1988b.

Appendix 3

The interview guide

1 Background questions

- Name, profession, age and sex.
- Current department and position.
- Time working in the current position. Previous career within the same organization.
- Academic education and professional career.

2 Duties/tasks

- What are your current tasks/responsibilities?
- What is your role in urban planning/at what level of planning are you involved?
- What planning issues do you give the highest priorities – traffic, infrastructure, housing, aesthetics, etc?
- What are the main constraints in your planning work – economy, time, policy, etc?
- What are the current building densities for residential housing? Within which limits is it allowed to vary? Is the trend that the density is increasing/decreasing?

3 Urban planning/design and climate

- Do you have an interests in questions related to climate adaptation and thermal comfort? Do you think it would be beneficial to include climate and comfort aspects in urban design?
- At which level(s) of the planning process is climatic issues considered?
- How much time do you spend on discussing climatic aspects in planning? Would you like to dedicate more/less time for these issues?
- Have you had any education (university, internal, post graduate, etc) regarding the link between urban design and urban micro-climate?
- Which tools – e.g. climatic maps, statistical weather data, computer softwares – are available to predict the effect of urban planning/design on the micro-climate? Where do you find these tools/ information?

- If the answers of questions 12–14 are no:
  – Why are climatic issues not considered?
  – What are the obstacles/constraints – lack knowledge, lack of tools, lack of climate data, etc?
- If you knew that you could improve the micro-climate in urban environments through urban design, would you be interested to incorporate these aspects in the planning process?
- Are clients/developers or the public demanding climate-conscious design?
- In your opinion, how could climate aspects be incorporated in urban development in the future?

Paper I

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Influence of urban geometry on outdoor thermal comfort in a hot dry climate: A study in Fez, Morocco

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Abstract

There are few studies on the microclimate and human comfort of urban areas in hot dry climates. This study investigates the influence of urban geometry on outdoor thermal comfort by comparing an extremely deep and a shallow street canyon in Fez, Morocco. Continuous measurements during the hot summer and cool winter seasons show that, by day, the deep canyon was considerably cooler than the shallow one. In summer, the maximum difference was on average 6 K and as great as 10 K during the hottest days. Assessment of thermal comfort using the PET index suggests that, in summer, the deep canyon is fairly comfortable whereas the shallow is extremely uncomfortable. However, during winter, the shallow canyon is the more comfortable as solar access is possible. The results indicate that, in hot dry climates a compact urban design with very deep canyons is preferable. However, if there is a cold season as in Fez, the urban design should include some wider streets or open spaces or both to provide solar access.
Keywords: Urban geometry; Thermal comfort; Microclimate; Urban cool island; Urban heat island; Urban design.

1 Introduction

Due to rapid urbanization in developing countries, environmental issues have gained increased attention in cities with tropical climates. As a consequence, the interest in the microclimate around buildings in urban areas has increased because it affects, among other things, outdoor and indoor thermal comfort, energy use for heating and cooling, and the dispersion of air pollution. In the urban environment, a comfortable climate is important for well-being and to attract people to public spaces. The best known characteristic of urban climate is that air temperatures are higher than those in the surrounding rural areas at night. Nocturnal urban heat islands as high as 12 K have been found in dense centres of large cities [1,2]. By day, most studies show small urban–rural differences. Other typical characteristics of the urban climate include lower average wind speeds than outside the city [1].

Urban geometry and thermal properties of urban surfaces have been found to be the two main parameters influencing urban climate [1,3]. The ratio between the height of buildings (*H*) and the distance between them (*W*) influences the amount of both incoming and outgoing radiation and also affects wind speeds. The nocturnal heat island has been shown to increase with the *H*/*W* ratio since the net outgoing longwave radiation decreases due to reduced sky view factor (SVF). High thermal capacity of urban surface materials also contributes to the nocturnal heat island as a large part of the incoming radiation during the day is stored in such materials and not released until the night [2]. The effect of anthropogenic heat from the heating and cooling of buildings and motor vehicles on urban air temperatures is normally low, although some exceptions in city centres have been reported [3]. Air pollution affects both incoming and outgoing radiation but the net effect on air temperatures has usually proved to be small [1,3].

Since urban form and the properties of surface materials have a strong influence on the microclimate around buildings, urban design is a promising area for improving the thermal comfort of outdoor environments. However, urban climate and outdoor thermal comfort are generally given little importance in the planning and design processes [4,5]. Often the urban planning regulations used in hot dry countries, most of which are in the developing world, are imported from temperate climates and are thus poorly adapted to the local climate. Additionally, they may be very inflexible and thereby restrict the possibility of climate-conscious urban design, (e.g. [6–8]). As a consequence, urban areas often become unnecessarily uncomfortable.

In a hot and dry climate, where the diurnal temperature range is large with cool nights, the high daytime temperature during summer is the main problem rather than the nocturnal heat island (even though the latter may reduce the efficiency of night ventilation of buildings in summer). Compact urban forms in hot dry regions – typically found in old city centers – are known to be well adapted to the climate [7,9,10]. There are, however, few studies from hot dry climates on urban microclimate. In the desert city of El-Oued (33°N) in Algeria, Bourbia and Awbi [11] reported only small daytime differences between urban and rural temperatures although the maximum temperature tended to decrease as the *H*/*W* ratio increased. In the hot, but humid, environment of Dhaka (24°N), Bangladesh, Ahmed [12] found that on average the daily maximum temperatures decreased, by 4.5 K when the *H*/*W* ratio increased from 0.3 to 2.8. However, in these studies the *H*/*W* ratios were within a limited range and very deep street canyons were not included.

From a thermal comfort point of view, climatic and physical factors other than air temperature are important. In outdoor conditions the radiant exchange of the human body with the environment is of special importance due to exposure to solar radiation, the cold sky-vault, and warm and cool urban surfaces. The other factors influencing thermal comfort – air movements and humidity – vary much more outdoors than indoors. There are, however, few studies into the relationship between urban geometry and thermal comfort in hot dry cities. Pearlmutter et al. [6] compared the energy exchange of the human body within and above an urban canyon with $H/W = 1$ in Dimona (31°N), Israel. However, this study was restricted to one type of canyon and no comfort index was calculated.

The aim of this paper is to investigate the influence of urban geometry on microclimate and thermal comfort at street level in a hot dry climate. This is done by comparing urban street canyons in two neighbourhoods, one with a compact and the other with a dispersed urban form. The comparison is made in Fez, Morocco, and includes both summer and winter. The study is based on field measurements of air and surface temperatures, air humidity and wind speed. Thermal comfort is assessed by calculating the physiologically equivalent temperature (PET), a comfort index which takes into account all the environmental parameters influencing thermal comfort – temperature, radiation, humidity and wind speed.

2 The city of Fez and the study areas

The city of Fez (33°58’N, 4°59’W) is located in the interior of Morocco in a valley situated between the Rif mountains to the north and the Atlas mountains to the south (Fig. 1). The climate (Fig. 2) is characterized by hot and dry summers and cold winters. Diurnal temperature swings are large; the mean range is 17– 34°C in July and 4–15°C in January. The temperature can, however, rise above 40°C in the summer, especially when the desert wind, *chergui*, is blowing from the Sahara, and fall below 0°C in winter. The rainfall maximum is in the winter period whereas the summer period is almost completely dry. The daily hours of bright sunshine varies between about 6 h in December and 11 h in July [13].

Fig. 1
The location of Fez in northern Morocco.

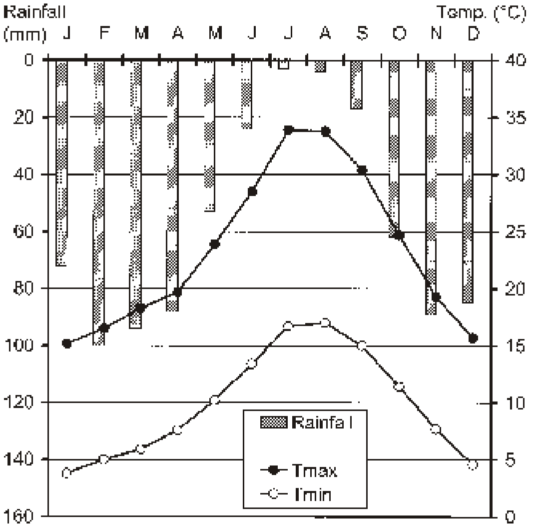

Fig. 2
Monthly mean maximum and minimum air temperatures and rainfall in Fez.

Source: Direction de la Météorologie Nationale, Morocco.

Fez was chosen for this study because it consists of two sections with a completely different urban form: the medieval city – the *medina*, hereafter referred to as the old city – and the contemporary city which has its roots in the time of French colonization – *nouvelle ville* or the new city [13–15].

The old city of Fez is extremely compact. The buildings, normally two to four storeys high, are inward looking with a courtyard in the centre. The streets are narrow and cut deep canyons through the city. No transport by car is possible except for a few distributor roads. The street network is irregular which increases the mutual shading by buildings. The shading at street level is further improved by the fact that in many places, the upper floors either protrude (e.g., bay windows) or bridge the alleyways.

The new city is a sharp contrast to the old city. Buildings are outward looking and the streets, which are designed for motor vehicles, are wide and provided with wide pavements. The street pattern is regular and, except for some tree-lined avenues and pedestrian arcades, there are few elements providing shade at street level.

3 Methodology

3.1 Selection of measurement sites

An area in the old and another in the new city were chosen for the measurement campaign in order to give two extremes of urban geometry. The studied area in the old city, situated at the core of the medina, has a compact urban form. Buildings occupy the whole plot, with the exception of space used for courtyards, and streets are narrow (Fig. 3). The residential part of the neighbourhood (locations 2–4 in Fig. 3) is one of the most densely built in the old city; three to four storey buildings are separated by 1.5–2.5 m wide alleys (Fig. 5). In the bazaar area (locations 1 and 5 in Fig. 3), however, streets are somewhat wider and the buildings are only one or two storeys. The

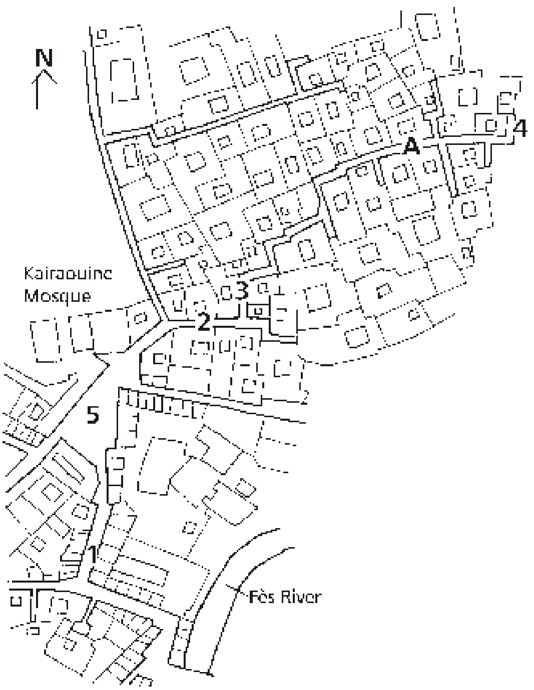

Fig. 3 *Site map from the studied area in the old city (the Seffarine district).*

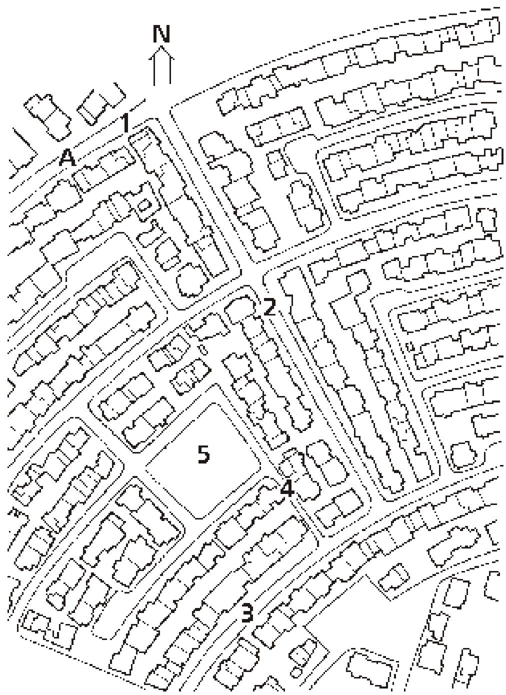

Fig. 4 *Site map from the studied area in the new city (the Adarissa district).*

studied area in the new city was recently built and has a dispersed urban form. This planned neighbourhood is very uniform in terms of street width and building height and the portion of the plot occupied by buildings is much smaller than in the old neighbourhood (Fig. 4). The two to three storey buildings are mainly semi-detached and

Table 1 *Geometric characteristics of the measurement locations in the two neighbourhoods*

Neighbour-hood	*Location*	*Average building height*	*Distance between buildings*	*H/W ratio*	*Orientation*
Old	A	13.6	1.4	10	E – W
	1	4	3.0	1.3	E – W
	2	13	2.3	—[a]	N – S
	3	13	2.3	6	E – W
	4	11	1.0	11	N – S
	5	6.5	11	0.6	N – S
New	A	10.5	19	0.6	NE – SW
	1	10	18	0.6	NE – SW
	2	12	17	0.7	NW – SE
	3	10	20	0.5	NE – SW
	4	11	10	1.1	NW – SE
	5	—	—	—	—[b]

a The first floor is bridging the alley.
b A square with some vegetation.

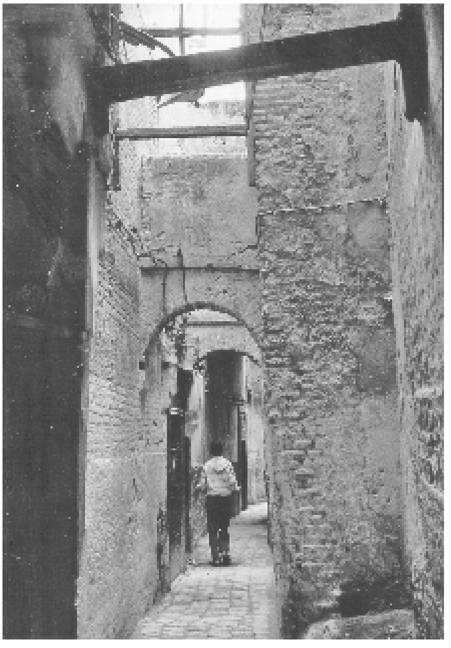

Fig. 5. A narrow alley in the residential part of the old neighbourhood (close to measurement location A in Fig. 3).

have both front and back yards (Fig. 6). Location 5 is a square. In both areas, measurement sites were chosen in order to represent differences in urban geometry (*H*/*W* ratio) and street orientation (see Table 1).

The chosen neighbourhoods are well suited for a comparison of the influence of geometry since, apart from the difference in urban geometry, they are similar. For instance, they have the same surface materials (plaster and brick, concrete and asphalt) and have virtually no artificial heat sources. The vehicle traffic is not intense and its impact on the residential areas has been shown to be negligible [3]. The fact that the altitude of the new neighbourhood is 140 m higher than the old neighbourhood has only a minor impact since the decrease in temperature with altitude (lapse rate) does not exceed 1 K/100 m [1].

Two street canyons are investigated in detail (see locations A in Figs. 3 and 4). The first is in the old city and, with a *H*/*W* ratio of 9.7,

Fig. 6
A street in the new neighbourhood (close to measurement location A in Fig. 4).

is henceforth called the "deep" canyon. The second is in the new neighbourhood and, with a *H/W* ratio of 0.6, is called the "shallow" canyon. Both streets are oriented in roughly the same direction and are surrounded by similar types of streets and buildings. The deep street canyon has its long-axis oriented approximately east–west and is bordered by buildings of uniform height. Part of this street is covered, but at the measurement site the street is exposed to the sky (Figs. 5 and 7). The shallow canyon has its long-axis oriented approximately northeast– southwest. Small trees are planted along the pavement and some houses have trees in the front yard (Figs. 6 and 8).

3.2 Field measurements

For each neighbourhood, the measurements were divided into long-term, continuous measurements at location A and short-term, instantaneous measurements at locations 1–5 and A (see Figs. 3 and 4):

- Location A: Continuous measurements were made at the deep and shallow street canyons over 1.5 years. The position of the measurement instruments are shown in Figs. 7–9. In the canyons, the instruments had to be put above pedestrian height in order to neither attract undue attention nor interfere with the traffic. In the case of the shallow canyon, the location of the air temperature and humidity instrument was quite far from pedestrian height – about 6 m (≈ 0.5H) above the street base and about 2 m from the northfacing wall. Despite this difference in level, several studies have shown that, except in the very near vicinity of canyon surfaces, the air temperature differences within the canyon are fairly small [6,16,17]. The surface temperatures sensors were embed-

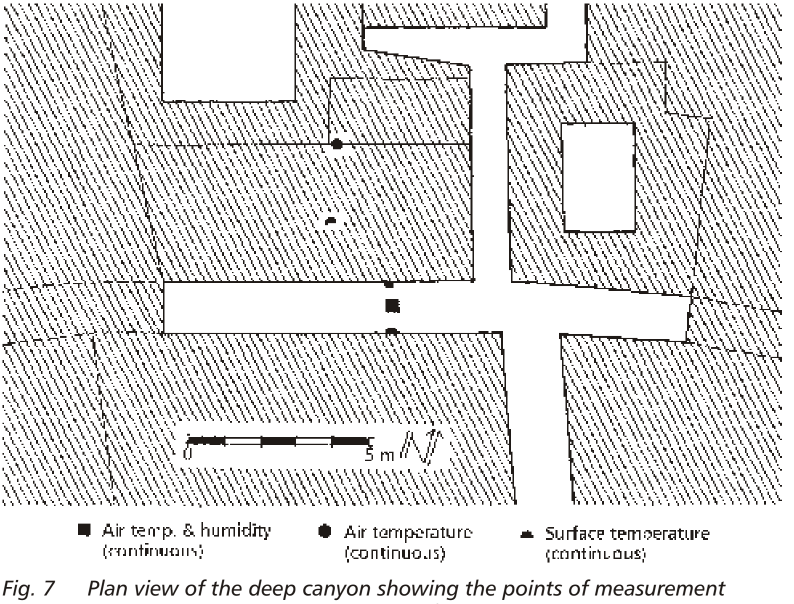

Fig. 7 Plan view of the deep canyon showing the points of measurement within the street and above the roof.

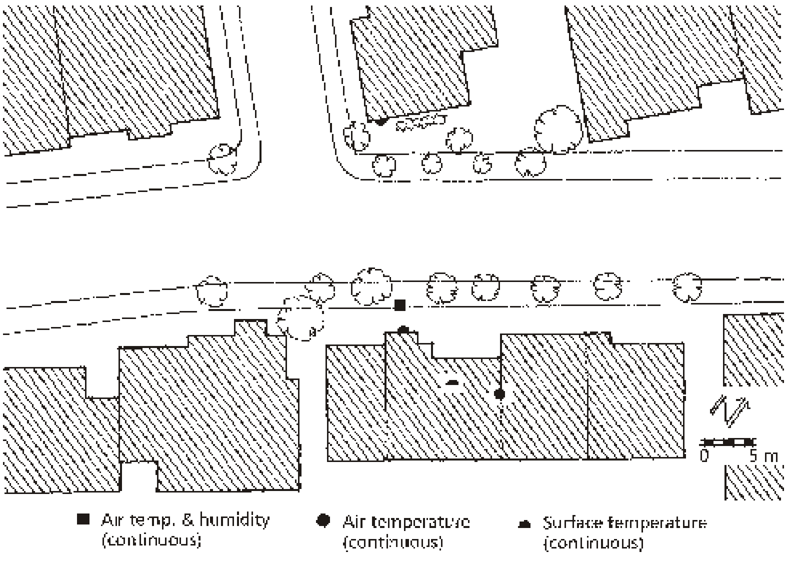

Fig. 8 Plan view of the shallow canyon showing the points of measurement within the street and above the roof.

ded in plaster of Paris. The miniature loggers for air temperature and humidity were shielded against solar radiation with a white plastic cover which was perforated to allow for air circulation. This protection however proved to be insufficient and gave air temperatures of up to 2 K above real values. Therefore, those recordings where the loggers were exposed to solar radiation have been subsequently corrected. In addition to the continuous measurements, instantaneous measurements (as described for locations 1–5 below) were performed simultaneously in each canyon during one summer and one winter week.

- Locations 1–5: Instantaneous measurements of air and surface temperatures, relative humidity and wind speed were performed in both neighbourhoods. Readings were taken over one summer and winter period three times per day: prior to sunrise; in the afternoon (14:00– 15:00 h); and in the evening after sunset.

The measurement periods are shown in Table 2 and the instruments used in Table 3.

Table 2 Measurement periods

Site	*Neighbourhood*	*Continuous*	*Instantaneous*
A	Old and new	Feb. 2000–Aug. 2001	2–6 Feb. 2000
			26–30 June 2000
1–5	Old		19–20 July 1998
			4–5 Dec. 1998
	New		17–18 July 1998
			6–7 Dec. 1998

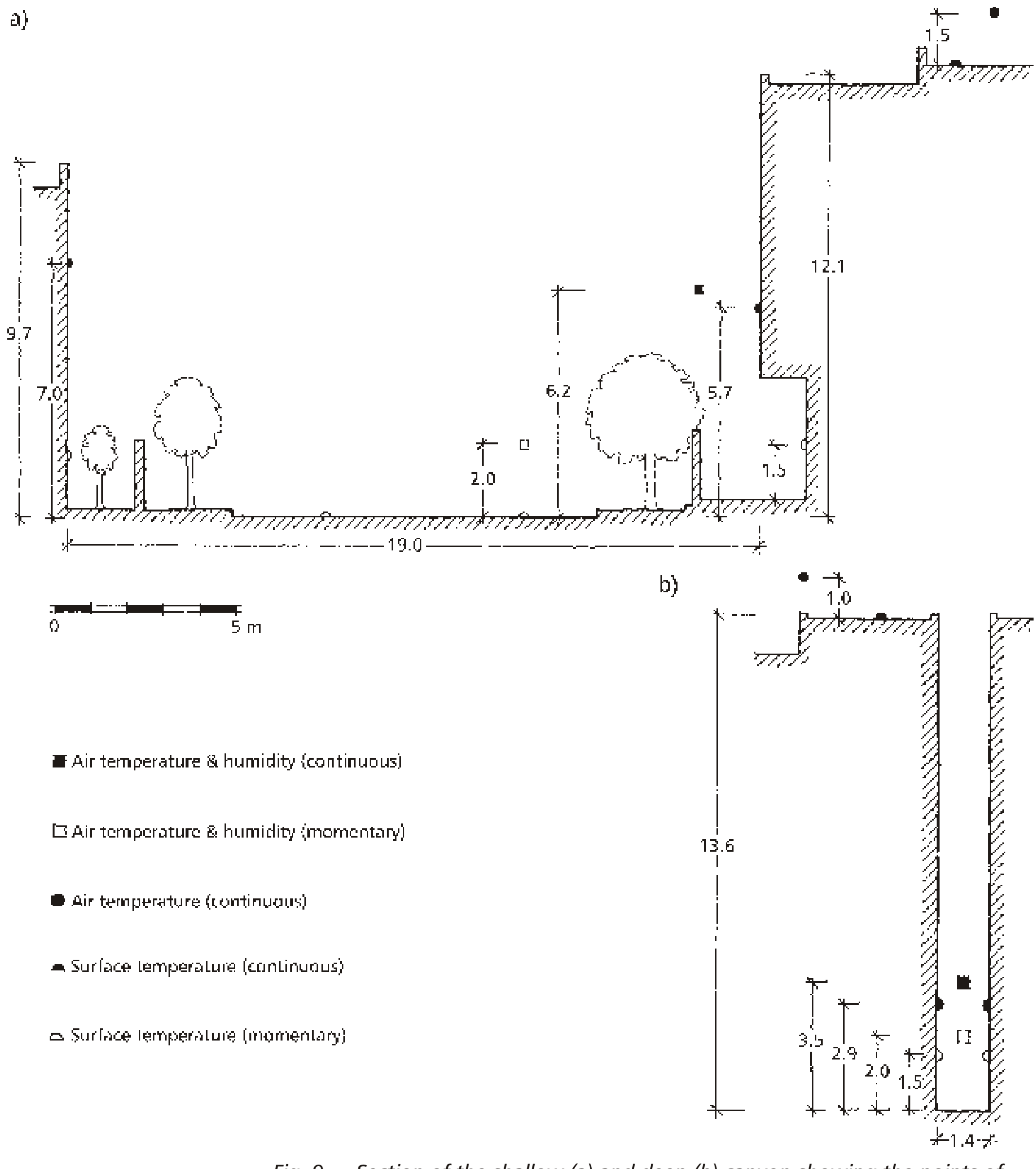

Fig. 9 Section of the shallow (a) and deep (b) canyon showing the points of measurement within the street and above the roof.

Table 3 Measurement instruments

Location	*Measured parameter*	*Instrument*
A	Canyon air temperature	Tinytag Plus miniature logger
	Canyon relative humidity	Tinytag Plus miniature logger
	Roof air temperature	PT100 sensor
	Surface temperatures (continuous)	PT100 sensor
	Surface temperatures (instantaneous)	Swema SWT 28
	Wind	Swema SWA31 (hot wire anemometer)
1–5	Canyon air temperature	PT100 sensor
	Canyon relative humidity	Rotronic OP100A
	Surface temperatures	Swema SWT 28
	Wind Swema	SWA31 (hot wire anemometer)

3.3 Assessment of thermal comfort

The thermal comfort was assessed for the deep and shallow canyons (location A in Figs. 3 and 4) by calculating the PET which is expressed in °C and takes into account air temperature, mean radiant temperature (MRT), humidity and wind speed. All necessary parameters to calculate PET were measured except shortwave (direct and diffuse) radiation for Fez which was taken from the software Meteonorm [21]. For the deep canyon, MRT was calculated according to the VDI guidelines [18], see Appendix. The canyon surfaces were assumed to be full radiators and the atmospheric emissivity, ε_a, was calculated as [1]

$$\varepsilon_a = 0.70 + 5.95 \times 10^{-5} \mathrm{VP} \exp(1500/T),$$

where VP and T are the vapour pressure (hPa) and temperature (K) of the air, respectively. The angle factors for a standing person were estimated using a graphical method [19]. Reflected radiation from the facades and the street has been ignored since most reflection takes place in the top of the canyon and is not likely to have a great effect at pedestrian level.

For the shallow canyon, which has a more complex geometry and where trees are present, MRT was calculated using the software RayMan 1.2 [20], which requires the solar radiation at the height of pedestrians (1 m above the ground). The approximate global radiation at the centre of the street was calculated as the sum of the direct and the diffuse components, where the diffuse radiation depends on the geometry of the street canyon and decreases with canyon depth:

$$I_g = I_{dir} + \mathrm{SVF} \times D,$$

where I_g is the global solar radiation (W/m^2), I_{dir} is the direct solar radiation (W/m^2), D is the diffuse solar radiation (W/m^2) and SVF is the sky view factor (at 1 m height). Note that reflections from the façades and the street are not considered. During periods of shade $I_{dir} = 0$ and the person receives only diffuse radiation.

The PET index was calculated with software annexed to [18]. The relationship between the PET index and thermal perception has only been defined for steady state conditions. Although clothing and activity levels are not taken into account in the calculation of PET, the correlation between PET and thermal perception depends on these parameters. For a standard indoor environment, the comfort zone for a resting person (activity = 80 W) with typical indoor clothing (0.9 clo) is defined as 18–23°C [22]. Since the relationship between PET and thermal comfort for other clothing and activity levels has not been defined, no comfort zone is applied in this study; instead the PET index is used to compare the two street canyons.

4 Results

4.1 Air temperature

The measured air temperatures in the two canyons (location A, Figs. 3 and 4) are shown in Figs. 10–13 together with the temperature at the airport which is assumed to be representative of the surrounding countryside. The results are shown for the warm summer period and the cool winter period. The summer period is defined on the basis of air temperature at the airport as being between 29 May and 16 September 2000. Over this period the maximum daily temperature consistently exceeded 30°C with few exceptions. The winter period is defined as February and December 2000 and January 2001.

During the afternoon, which is the warmest part of the day, the deep canyon was markedly cooler than the shallow one. This difference was observed all year round (Fig. 10), but was especially pronounced during summer (Fig. 11). During the warm season, the average difference in maximum daytime temperatures between the two canyons was 6 K. In general the difference was highest on warm, sunny days (the maximum recorded temperature difference between the canyons during the summer period was 15 K). Fig. 12 shows that the deep canyon was, on average, 10 K cooler for the 15 warmest days of the summer period (all of which had temperatures at the airport exceeding 39°C).

The reason for the large daytime cool island of the deep canyon is related to its high height to width ratio ($H/W = 9.7$). By day, the lower part is in complete shade and, consequently, surfaces remain cool and the air is not warmed up. Furthermore, by day the warm air above the roofs is unable to reach the lower parts of the canyon both because the main air flow above the roofs skims over the deep canyon (see e.g. [1]) and there the air is more buoyant than the cool air in the canyon below. By night the cooling of the surfaces at the canyon bottom is very weak. However, the roof-tops cool down efficiently through radiative cooling. The resulting cooled air packets formed above the roofs may enter the canyon, as suggested by, e.g., Givoni [10] and could thus contribute to the cooling of the canyon air. Such cool air drainage is made possible by the fact that the roofs close to the measurement site have very low parapets. This could explain the surprisingly low nocturnal temperatures in the deep canyon on the 15 warmest days (Fig. 12) since most of these days also had clear nights leading to very efficient radiative cooling of the roof

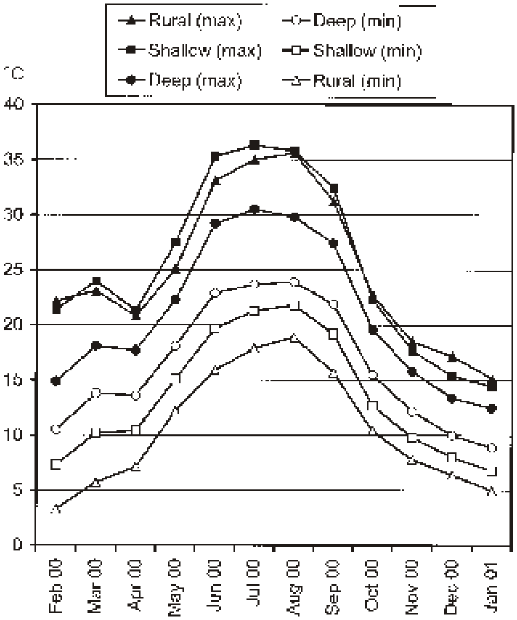

Fig. 10 Monthly mean maximum and minimum air temperature in the deep and the shallow canyons as well as at the rural station (Fez airport) during the period between February 2000 and January 2001.

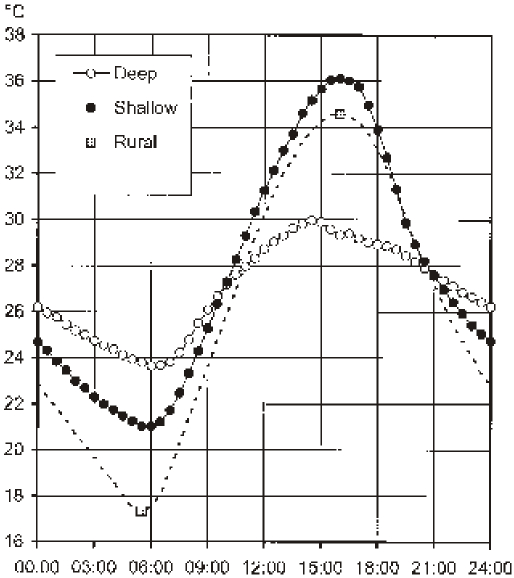

Fig. 11 Average air temperatures for the summer period in the deep and shallow canyons as well as for the rural station.

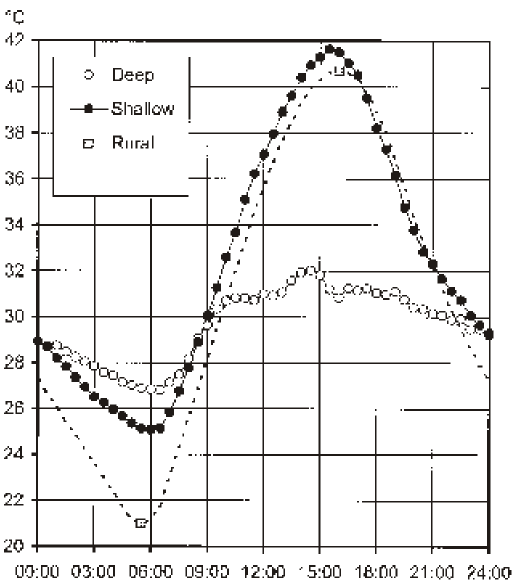

Fig. 12 Average air temperatures for the 15 hottest days in the summer in the deep and shallow canyons as well as for the rural station.

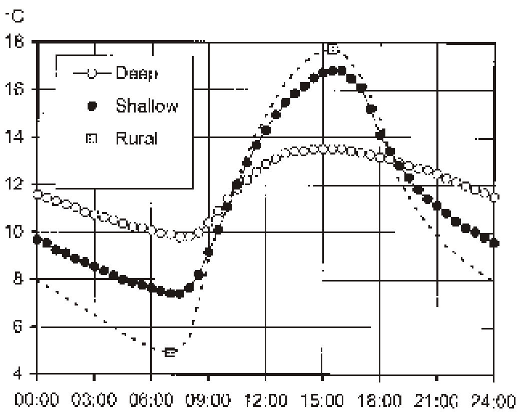

Fig. 13 Average air temperatures for the winter period in the deep and shallow canyons as well as for the rural station.

tops. However, it cannot be excluded that cool air also enters the canyon by horizontal air movements.

During the night, the deep canyon had higher air temperature than the shallow one (Figs. 11–13), which was to be expected because of the much lower SVF of the deep canyon. However, compared to observations in other urban areas with similar SVFs, the nocturnal heat island in the deep canyon was modest [1,2].

During the winter period the difference between the canyons was less, see Fig. 13. The difference in maximum temperature by day was only about 3 K, which is due, at least partly, to more rainy and overcast days (on rainy days there was virtually no difference between the canyons).

Table 4 Relationship between afternoon air temperatures and H/W ratio in the old neighbourhood for a winter and a summer day (recorded at around 15:00 on 19 July and 5 December 1998).

		Temperature (at 15:00) (°C)	
Site	*H/W ratio*	*Summer day*	*Winter day*
Bazaar area (sites 1 and 5)	0.6–1.3	36–42	16–17
Residential area (sites 2–4)	6–11	30–31	13–14
Airport	N/A	38	15

The short-term, instantaneous measurements at locations 1–5 of each neighbourhood confirmed the trend that the maximum air temperature decreases with increasing *H/W* ratio (see Table 4). Thus, in the old neighbourhood, a difference in maximum air temperature as great as 10 K was found between the dense residential parts and the more open bazaar area which is only 100–150 m distant. In the dispersed neighbourhood, where all streets have a similar *H/W* ratio, the temperature differences were insignificant including the square (location 5). No significant influence of the orientation of the streets on the air temperatures could be found in either of the neighbourhoods. In the old neighbourhood the reason is probably that the alleys are so narrow and winding that solar radiation seldom penetrates irrespective of street orientation. In the new neighbourhood, on the other hand, the streets are so wide that temperature differences between streets will most likely be levelled out by horizontal air transportation (microadvection, see e.g. [23]).

The above canyon air temperatures were similar in both areas during summer as well as winter.

4.2 Surface temperatures and mean radiant temperature (MRT)

The surface temperatures of the façades of the deep and shallow canyons (location A, Figs. 3 and 4) are shown in Figs. 14 and 15 (continuous measurements) for the summer and winter periods, respectively. Note that the summer period is represented by June (deep canyon) and July (shallow canyon) 2000 and the winter period by 2–11 February 2000 because of an incomplete data series.

The deep canyon had low and stable surface temperatures, which is due to the almost complete shade and low SVF which re-

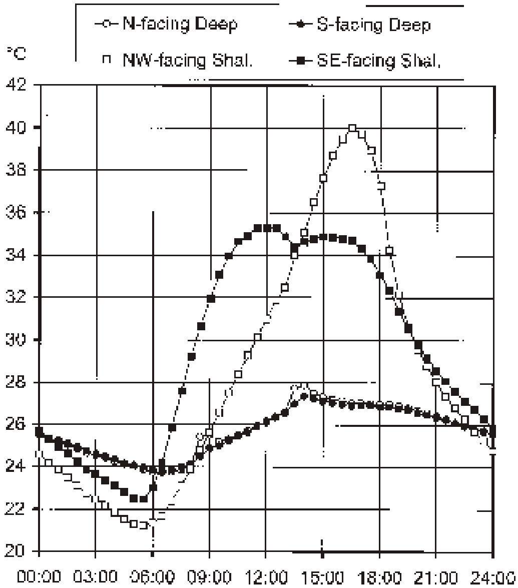

Fig. 14 Average surface temperatures for June 2000 in the deep canyon and July 2000 in the shallow canyon.

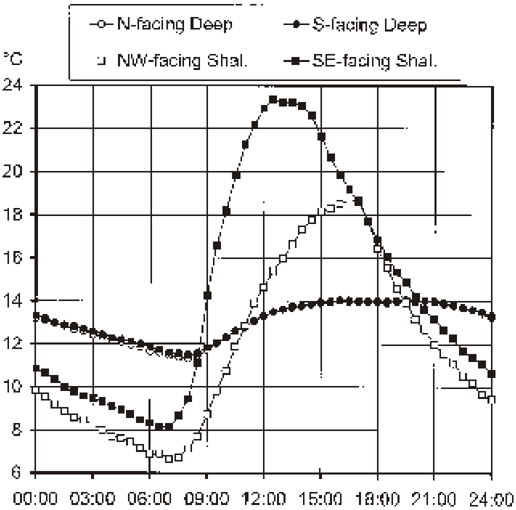

Fig. 15 Average surface temperatures for the period 2–11 February 2000 in the deep and shallow canyons.

duces both incoming shortwave radiation by day and radiative cooling by night. Note, however, the slight increase in temperature on the north-facing façade in June, this is the result of short periods of solar exposure at around 09:00 and 14:00 h. The instantaneous measurements of surface temperatures were similar to the continuous measurements.

The shallow canyon had large variations in surface temperatures, which is explained by differences in orientation, surface reflectivities, height above the street and time of the day. The instantaneous measurements, which were made at a lower height, showed lower façade temperatures than the continuous measurements by day and higher by night. This can be explained by the vegetation along the lower parts of the façades which reduce both incoming solar radiation and nocturnal radiative cooling. The street was the warmest surface, especially in the summer; in June temperatures could reach 50°C. Exposed surfaces such as the street and the upper parts of the façades cooled during the night due to the large SVF.

The MRT for a person standing in the middle of the street was the parameter most strongly linked to the H/W ratio. In the deep canyon, the MRT was very stable since the person would be almost constantly in shade during the day and by night the exposure to the sky vault is limited (due to low SVF) and surface temperatures are stable. For the summer period, the average daily MRT varied between 25 and 28°C except at 14:00 h when a peak of 38°C occurred due to a short period of solar penetration. In the shallow canyon, however, the MRT had large diurnal swings. This is because the subject is exposed to solar radiation for most of the day and the cold sky vault at night. Moreover, the canyon surfaces are warm by day and cool by night. For the summer period, the average MRT varied between 16 and 63°C.

4.3. Humidity and wind speed

The relative humidity was very stable in the deep canyon but had considerable diurnal variation in the shallow canyon, both in summer and winter (see Figs. 16 and 17). This is explained, for the most part, by the diurnal variation in air temperature in the two canyons. The vapour pressure was on average about 1 hPa higher in the deep canyon in both seasons. The wind speed varied greatly from day to day and according to the time of the day. As expected, the wind speeds were lower and more stable in the deep canyon. The average wind speed in the deep canyon was 0.4 m/s during both the summer and the winter measurement periods. The shallow canyon had an average wind speed of 0.7 m/s in summer and 0.8 m/s in winter.

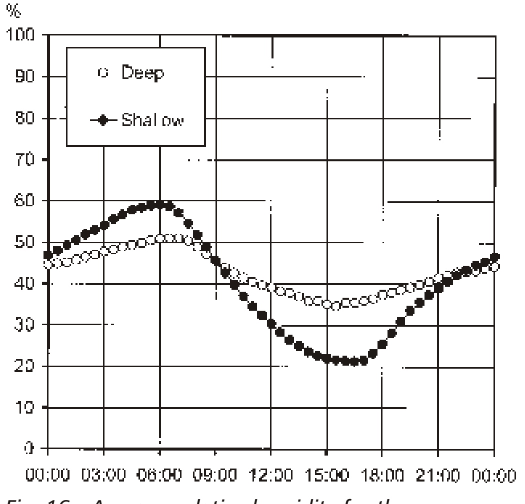

Fig. 16 Average relative humidity for the summer period in the deep and shallow canyons.

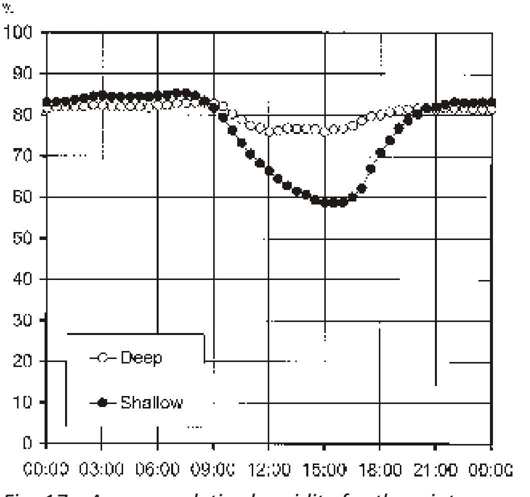

Fig. 17 Average relative humidity for the winter period in the deep and shallow canyons.

4.4 Outdoor thermal comfort

The calculated PET for the summer and winter periods defined above are shown in Figs. 18 and 19. The wind speeds were assumed to have constant values of 0.4 m/s in the deep canyon and 0.8 m/s in the shallow canyon during both seasons.

There was a considerable difference between the two canyons. In summer the PET values in the deep canyon are very stable between 23 and 28°C. These moderate values are mainly explained by low air temperature and low MRT. Note, however, the peak at 14:00 h: this is the time when the solar beam reaches the street level during the period mid-May – mid-July. In contrast for the shallow canyon, the PET values were extremely high in the summer exceeding 40°C between 11:00 and 17:00 h. The reason is the combined effect of very high air temperatures and high MRT. In winter the deep canyon had low PET

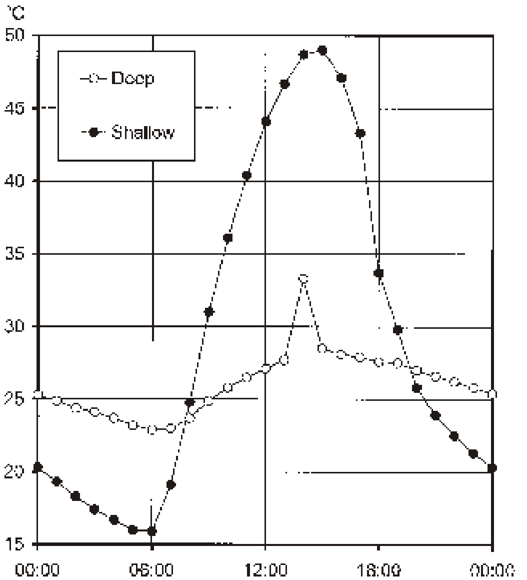

Fig. 18 Physiologically equivalent temperatures (PET) for the summer period in the deep and shallow canyons.

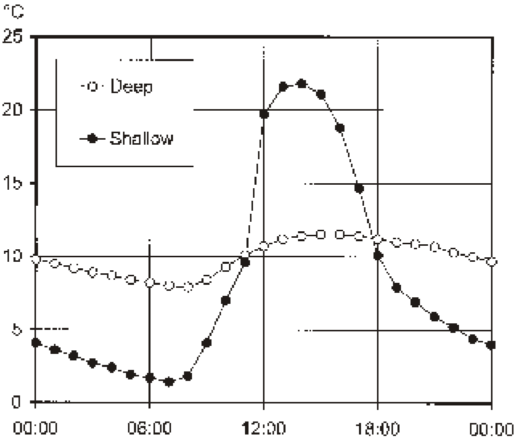

Fig. 19 Physiologically equivalent temperatures (PET) for the winter period in the deep and shallow canyons.

values, both during day and night, due to low air temperature and a total lack of solar access. In winter, the shallow canyon has even lower PET values during the night than the deep canyon, due to low temperatures and the exposure to the cold sky vault, but PET reaches “comfortable” values in the afternoon, due to the access to solar radiation.

It should be noted that in reality a person in the shallow canyon has the option of moving between sunny and shady places. However, this is only really possible during the cold season; in the summer, when the solar elevation is high, it is almost impossible to find shade. In the winter season, the discomfort in the deep canyon could be compensated for to some extent by heavier clothing, but the total lack of solar access at pedestrian level contributes to discomfort.

5 Discussion

5.1 Influence of urban geometry on the microclimate and outdoor thermal comfort

The results show a clear relationship between urban geometry and the microclimate at street level. The air and surface temperatures found in the shallow canyon (*H*/*W* = 0.6) agrees well with other studies with similar *H*/*W* ratio at similar latitudes [6,11,16]. As the H/W ratio increases, so does the minimum temperature, which can be expected as the SVF decreases [1]. The maximum temperature, however, decreased with increasing H/W ratio. The latter phenomenon is less well documented but was also found by, for instance, Ahmed [12].

The very deep canyon (*H*/*W* ≈10) has a very unique microclimate from both the climate above the canyon and streets with low *H*/*W* ratios. The huge difference in daytime temperature found here between the deep and the shallow canyons has not been reported in other studies. The well defined daytime cool island of the deep canyon is obviously an advantage during the warm season, especially since the cooling effect is greatest on extremely hot days (Fig. 12). The nocturnal temperature is higher in the deep canyon compared to the shallow canyon, but the relative cooling by day exceeds the warming by night. The negative effect of the nocturnal heat island during the summer is thus limited and cooling of buildings during the night is possible.

When combining all the environmental parameters influencing thermal comfort into the physiologically equivalent temperature (PET), the differences between the deep and the shallow canyon are still large. In this study, no comfort zone was presented because the levels of clothing and activity vary from those of the defined comfort zone for PET, and because several studies have shown that the perception of thermal comfort differs between indoors and outdoors (see e.g. [24,25]). In general, people seem to accept more extreme temperatures outdoors than indoors. A thorough study is needed in order to better assess human comfort, and to define the comfort zone, in a hot dry climate. Such a study would be based on both climate measurements at pedestrian level and interviews with subjects. Moreover, it should include public spaces which are frequently visited and where outdoor activities take place.

5.2 Climate-conscious urban design in a hot dry climate

The fact that urban geometry strongly influences the microclimate and the thermal comfort at street level has implications for urban planning and design in a hot dry climate. This study shows that a compact urban form with very deep street canyons gives a good protection during the long, hot summer period as such a design results in lower temperatures (cool island) and provides shade for pedestrians during the warmest part of the day. A dispersed urban form, on the contrary, was shown to create an extremely uncomfortable environment in the summer. However, there are also disadvantages with a compact urban form, especially the poor thermal comfort in the winter, a season which is quite cold in many hot dry cities.

Consequently, a climate-conscious urban design should have a compact urban form with deep street canyons but, for cities with a cold winter as in the case of Fez, it should also include some wider streets or open spaces or both to allow solar access. Such open spaces, which function as sun-spots in the winter, require solar protection at pedestrian level in the summer. This can be achieved through shade trees, projection of the upper floors, arcades or any other types of horizontal shading device designed in such a way that they allow solar radiation to penetrate in the winter while providing shade in the summer. In order to keep surface temperatures as low as possible, light-coloured paving materials and façades should be used.

A climate-conscious urban design in hot dry climates would require a change of the currently existing urban design practise and regulations, which favours a more dispersed urban form [7,9]. However, a shift to a more compact grouping of buildings would have several consequences. The positive effects include – apart from improved microclimatic conditions – a more comfortable indoor climate and reduced need for cooling, more efficient land use and less expensive infrastructure. Possible negative effects include less solar exposure in winter, reduced accessibility for both emergency vehicles and private cars, and overcrowding. Further studies are needed in order to promote urban planning and design in hot dry climates that takes microclimate and outdoor thermal comfort into account without creating serious side effects. Apart from revising the existing urban codes, there is a need to establish climate-sensitive urban design guidelines. This, in turn, would require simulations on how urban form influences the urban climate and human comfort. There is also a need to develop simple, user-friendly tools which would help planners, urban designers and architects in carrying out a climate-conscious urban design.

Acknowledgements

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Appendix

In this study, the mean radiant temperature (MRT) was calculated according to the VDI guidelines [18]:

$$\mathrm{MRT} = \left[\mathrm{MRT}^{*4} + \frac{f_p a_k I_b}{\varepsilon_p \sigma}\right]^{0.25},$$

where f_p is the surface projection factor of a standing or walking person, I_b the beam radiation (on a plane perpendicular to the beam)

(W/m^2), a_k = average (shortwave) absorptivity of the human body = 0.7, ε_p the emissivity of the human body = 0.97, σ is = 5.67×10^{-8} W/m^{2}K^4 (the Stefan–Boltzmann constant).

The MRT*, which is the MRT from longwave and diffuse shortwave radiation (not including direct beam radiation) from all the surfaces in the canyon, was calculated as

$$\mathrm{MRT}^* = \left[\frac{1}{\sigma}\sum_{i=1}^{n}\left(\varepsilon_i \sigma T_{si}^4 + \frac{a_k D_i}{\varepsilon_p}\right)F_i\right]^{0.25},$$

where ε_i is the emissivity of each surface, T_{si} the temperature of each surface (K), D_i the diffuse radiation from each surface (W/m^2), F_i is the angle factor of each surface.

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Paper II

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Influence of urban morphology and sea breeze on hot humid microclimate: the case of Colombo, Sri Lanka

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Abstract

Urbanisation leads to increased thermal stress in hot-humid climates due to increased surface and air temperatures and reduced wind speed. We examined the influence of urban morphology and sea breeze on the microclimate of Colombo, Sri Lanka. Air and surface temperatures, humidity and wind speed were measured at 1 rural and 5 urban sites during the warmest season. The urban sites differed in their height to width (H/W) ratio, ground cover and distance to the sea. Intra-urban air temperature differences were greatest during the daytime. A maximum intra-urban difference of 7 K was recorded on clear days. Maximum temperatures tended to decrease with increasing H/W ratio and proximity to the sea. All urban sites experienced a nocturnal urban heat island (UHI) when the sky was clear or partly cloudy. The temperature differences between sunlit and shaded urban surfaces reached 20 K, which shows the importance of shade in urban canyons (reducing long-wave radiation from surfaces). Within the urban areas, the vapour pressure was high (>30 hPa) and showed little diurnal variation. Wind speeds were low (<2 m s^{-1}) and tended to decrease with increasing H/W ratio. Shading is proposed as the main strategy for lowering air and radiant temperatures; this can be achieved by deeper canyons, covered walkways and shade trees. It is also suggested to open up wind corridors perpendicular to the sea to facilitate deeper sea breeze penetration.
Keywords: Urban geometry, Tropical climate, Climate-sensitive urban design, Urban heat island, Coastal city structure.

1 Introduction

The hot-humid tropics are experiencing unprecedented urban growth rates (Emmanuel 2005). It is thought that this period of urban transformation in the hot humid region will be completed in a period of <60 yr (1950–2010) (cf. WCED 1987, Oke et al. 1990/91, Jáuregui 1997).

Environmental changes brought about by urbanisation have been studied by researchers in medicine, agriculture, geography and climatology (cf. Harrison & Gibson 1976, Lake et al. 1993); however, application of this knowledge in the field of urban planning and design has been limited (see e.g. Eliasson 2000). Problems such as increased energy use in buildings and deteriorating human comfort have received very little attention among urban planners and designers. This is especially the case in tropical cities, where urbanisation is at its peak. Considering the importance of cities in the national economies of developing tropical countries, a deterioration in the quality of life in tropical cities is likely to have an adverse effect on the respective national economies.

1.1 Urban morphology and climate

Cities have a *nocturnal* urban heat island (UHI) which tends to be more intense in the densely built, downtown area than in the suburbs. Traditionally, the thermal properties of building materials were thought to be the primary cause for this urban climate anomaly. However, evidence indicating the importance of urban geometry to the creation and the magnitude of the UHI phenomenon began to accumulate in the 1970s. Terjung & Louie (1973) were among the first to suggest that the urban–rural daytime temperature anomaly is largely attributable to the aspect of vertical surfaces to the sun.

Comparing the UHI effect of thermal properties and urban geometry, Oke (1981) found no significant correlation between types of man-made surfaces and UHI intensity. The only significant difference observed was between man-made and natural surfaces. Thus, concrete surfaces and asphalt paving, brick and concrete block walls, all contribute more or less equally to the problem of urban heat build-up, while tree-covered areas show a remarkable reduction in heat build-up. A comparison of nocturnal UHIs and urban geometry showed that UHI intensity increases with increasing height to width (H/W) ratios of street canyons (see e.g. Oke 1981, 1988). However, Oke (1988) argued that non-geometrical factors such as heat capacity and anthropogenic heat release may also influence UHI intensities.

Todhunter (1990) took the position that, at the micro-scale, urban geometry was more important in explaining the spatial-temporal distribution of UHIs than surface materials. However, he argued that both the geometry and surface thermal characteristics played an equal role at the meso-scale.

Arnfield (1990) and Oke et al. (1991) carried out some of the earliest comparisons of the causes of the nocturnal UHI. Their numerical simulation studies concluded, inter alia, that

- Canyon geometry on its own is capable of giving rise to variations in nocturnal cooling which can generate a UHI.
- The magnitude of the UHI also depends on the differences in thermal properties between urban and rural areas. Higher soil moisture (and thus higher heat storage capacity and thermal admittance) makes the rural surroundings less different from urban surfaces. This may explain the lower UHIs found in many tropical cities.
- The presence of clouds, which increase the sky emissivity, results in weaker nocturnal UHIs as well as decreasing differences between different canyon forms.

1.2 Urban climate anomaly in tropical cities

Tropical nocturnal UHIs tend to be lower than in temperate climates (Jonsson 2005). Moreover, while the UHIs in temperate climates tend to be greater in the summer than in the winter, the seasonal difference in tropical regions is related to the wet and dry seasons (Arnfield 2003, Jonsson 2005). The nocturnal UHI is strongest during the dry season (e.g. Adebayo 1991, Jáuregui 1997, Jonsson 2005). The main reason is believed to be the smaller urban–rural differences in thermal properties because of more humid rural surroundings (higher humidity increases the heat capacity of soil; see also Oke et al. 1991).

Although the nocturnal UHI is well studied, the daytime urban climate has received less attention. In general, the urban–rural differences are smaller by day than by night, and the city can be either warmer or cooler than the rural surroundings (Arnfield 2003, Emmanuel 2005). Shade can lead to a daytime cool island (Oke et al. 1991, Johansson in press) in deep canyons. In their review of tropical UHI studies, Jonsson (2005) reported both daytime heat and cool island observations.

Hot climates tend to lead to larger intra-urban thermal differences than do cooler climates (Emmanuel 1997). The variation in urban microclimate and its implications on thermal comfort in the hot-humid tropics are discussed in Emmanuel (2005).

1.3 Aim of the study

Although the number of UHI studies in tropical cities has increased in recent decades (Arnfield 2003), they are still few compared to the number in temperate climates, especially concerning the influence of urban design on the daytime urban microclimate.

This study empirically examines the microclimate effects of the existing urban morphology of Colombo, Sri Lanka, and highlights some adaptation strategies that could improve the microclimate at street level. This study concentrates on climatic aspects; the effect of the microclimate on human comfort, including the calculation of an outdoor thermal comfort index, is presented in Johansson & Emmanuel (in press).

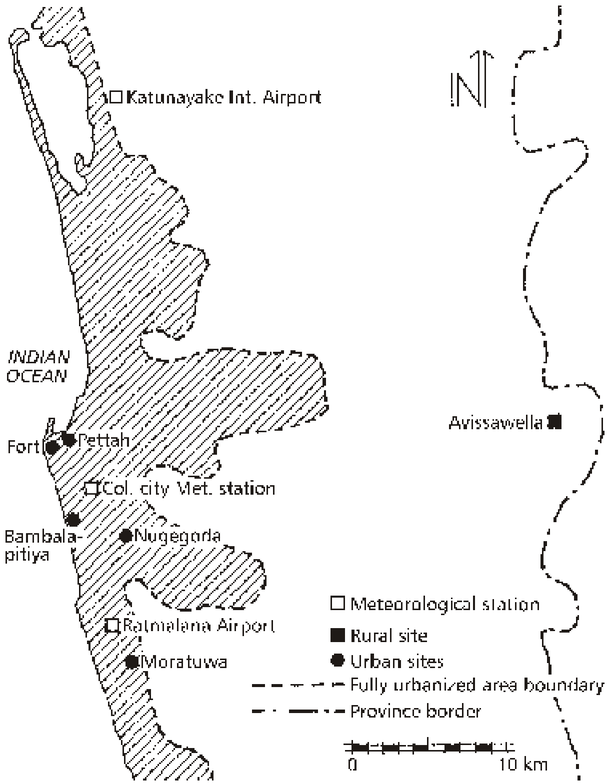


Fig. 1
Colombo (6° 54′ N, 79° 52′ E) with suburbs and locations of the measurement sites and official weather stations.

2 Study area

The city of Colombo (Fig. 1) is located at 6°54'N, 79°52'E on Sri Lanka's West coast. The municipal area of the city, which had a day-time population of 0.65 million in 2001, is in the center of the largely urbanized Colombo Metropolitan Region (CMR) of 5.3 million inhabitants. The CMR, which covers 3 administrative districts (Colombo in the center, Gampaha to the N and E, and Kalutara to the S) has an N–S extent of about 100 km and extends 40 km inland.

2.1 Urban structure

Colombo has low building density with high green cover and many low-rise buildings. Due to the natural limits to the West (Indian Ocean) and the East (extensive marshlands), the city has generally grown in a N–S direction along the national highways (Fig. 1). The combination of wide streets and low-rise buildings results in low H/W ratios, except in the central business district (the old colonial Fort area) and the old commercial quarters (Pettah). The former is characterized by high-rise buildings with some very high tower buildings, while the latter is characterized by a continuous built up street frontage of medium-rise buildings (3 to 4 stories) on narrow streets. The main transport axis in the city, Galle Road, runs N–S some 200 m parallel to the coast and is bordered by medium-rise buildings along much of its length within the city.

The ground cover and amount of vegetation vary greatly between neighborhoods, from an almost complete canopy cover in exclusive residential neighborhoods to paved/asphalted streets with few trees in less affluent sectors. The city has only a few parks. The outskirts of Colombo can be characterized as semi-urban; buildings are mainly positioned along the roads and the areas in between consist of agricultural land, including paddy and cash crop fields, marshes, open areas and water bodies.

2.2 Climate conditions[1]

Colombo is a lowland region with a typically hot-humid climate that is affected by the seasonal wind reversal of the Asiatic monsoon. The monsoon blows from the SW from late May to late September and the NE from late November to mid February. Air temperature and humidity are high throughout the year (see Fig. 3). Wind speeds are low, especially during the inter-monsoon periods of March to April and October to November. The annual rainfall is 2300 mm, with 2 seasonal peaks (see Fig. 3). Solar radiation is intense under clear sky conditions. However, there is a high probability of cloud development, especially during the afternoon. The mean daily sunshine duration varies between 5 h in June and 9 h in February.

3 Methods

3.1 Selection of measurement sites

Based on the geographical features of the city, we predicted that the main variables influencing the urban climate in the city of Colombo would be morphology, land cover characteristics and the distance from the sea. We selected 6 measurement sites to reflect these variables, 5 within the city of Colombo and its suburbs and 1 rural site (see Fig. 1). The urban sites represent different neighborhoods ranging from dispersed, low-rise suburban areas to densely populated downtown areas and the high-rise business district (Fig. 2). The following land cover classes were studied: buildings, hard surfaces (asphalted roads and paved surfaces) and green cover. Except for the sea, there were no water bodies in the vicinity of the selected sites. The rural site, situated in an agricultural area some 30 km east of Colombo, was surrounded by rubber plantations. Land cover information for a radius of 200 m around each site, was obtained from aerial images and Computer Assisted Design (CAD) drawings. The latter consist of polygons which indicate the areas covered by buildings, roads/hard surfaces and water bodies. Information about the vegetation was assessed from aerial photographs. The characteristics of the sites are given in Table 1.

The ground cover around each measurement site varied, but the surface materials within the urban canyons were similar. With the exception of the University of Moratuwa (UoM) site, which had a

1 Based on data from Colombo city station, 1970–2004 (Department oc Meteorology, Sri Lanka).

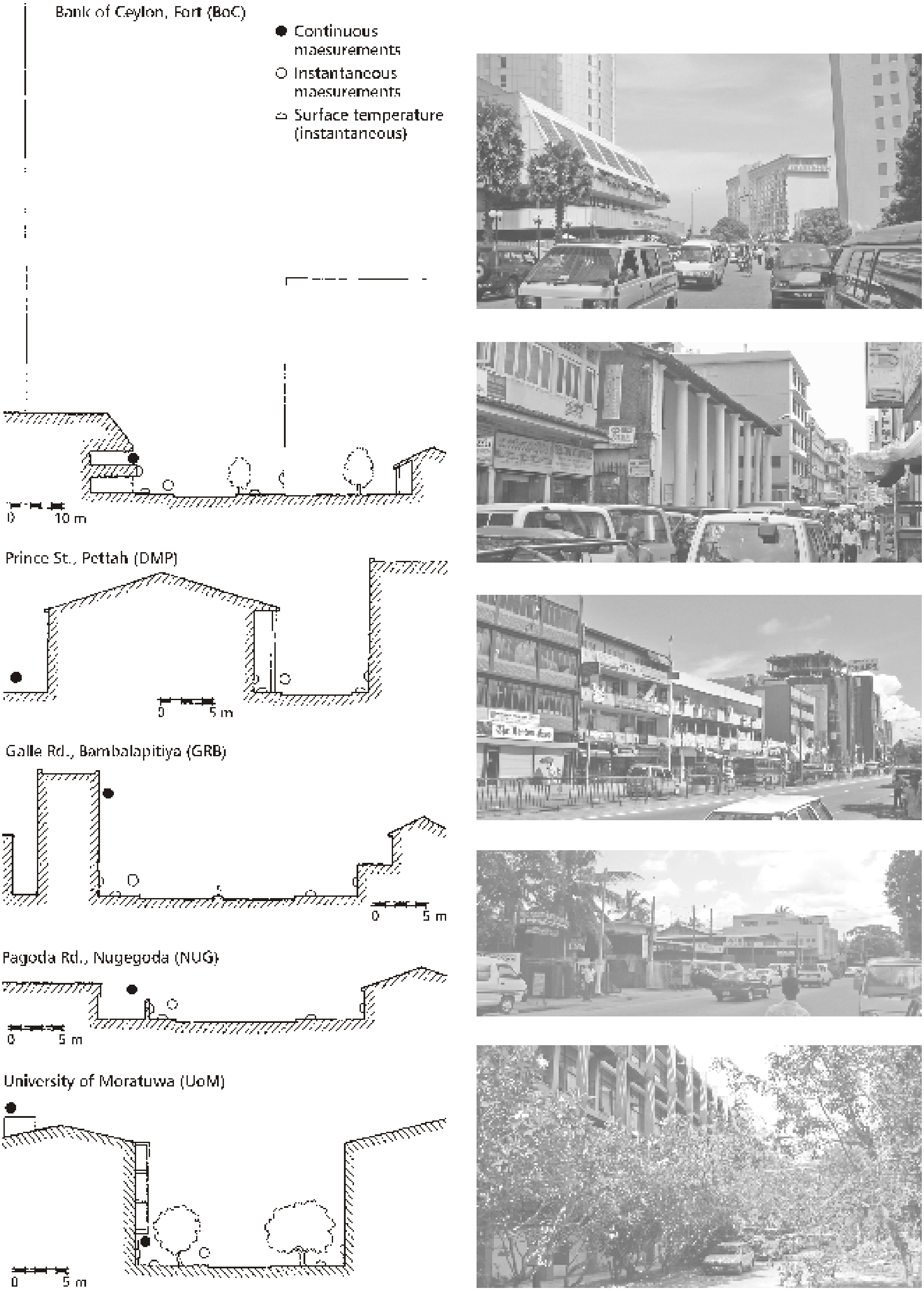


Fig. 2 Positioning of measurement equipment within urban canyons. BoC: Bank of Ceylon, Fort; DMP: Prince Street, Pettah; GRB: Galle Road, Bambalapitiya; NUG: Pagoda Road, Nugegoda; UoM: University of Moratuwa.

Table 1 Land use and ground cover of measurement sites and their surroundings. See Figs. 1 & 2 for locations and abbreviations.

Site	General description	Land use	Buildings	Ground cover (%)[a] Built-up	Roads and paving	Green
BoC	Downtown location, central business district. Close to sea-shore, some trees	Commercial/ office	High-rise, some very high towers	40	55	5
DMP	Downtown location, old commercial quarters, just E of Fort. Away from shore, almost devoid of vegetation	Commercial/ residential	Medium-rise (3–4 stories)	60	40	0
GRB	Commercial sector S of Fort, some trees. Close to sea shore, but buildings act as a barrier to sea breeze	Commercial/ office/ residential	Low- to medium-rise (1–4 stories)	35	55	10
NUG	Mixed-residential sector SE of city centre. Away from sea	Residential	Low-rise	30	50	20
UoM	Low-density, suburban location S of city. Away from sea	Institutional	Medium-rise	20	20	60
RUR	Rural, inland rubber plantation area	Agricultural	—	<5	0	>95

a Calculated for a radius of 200 m around each site.

Table 2 Street canyons where measurements were taken (for site keys, see Table 1). H/W: height to width ratio; SVF: sky view factor.

Site	Type of street	H/W [a]	SVF [b]	Orientation	Vehicle traffic	Ground cover Paving	Road	Green	Distance to sea [d] (km)
BoC	Commercial, medium sized street	0.8	0.49	E/W	Medium	Concrete	Asphalt	Some	0.2
DMP	Commercial, narrow street	1.2	0.31	ENE/WSW	Low [c]	Concrete	Asphalt	None	0.5
GRB	Commercial, 6-lane highway	0.3	0.65	NNW/SSE	High	Concrete	Asphalt	Little	0.3
NUG	Residential, main road through neighborhood, medium sized street	0.1	0.75	NNE/SSW	Medium	Asphalt	Asphalt	Little	4
UoM	Institutional, narrow street	0.5	0.44	E/W	Low	Concrete	Gravel	Some	3

a Approximate values (average).
b Calculated by RayMan (Matzarakis et al. 2000) at center of road, based on 3D information, taking into account buildings and trees.
c Restricted vehicular, but lively pedestrian, traffic.
d Shortest distance perpendicular to sea.

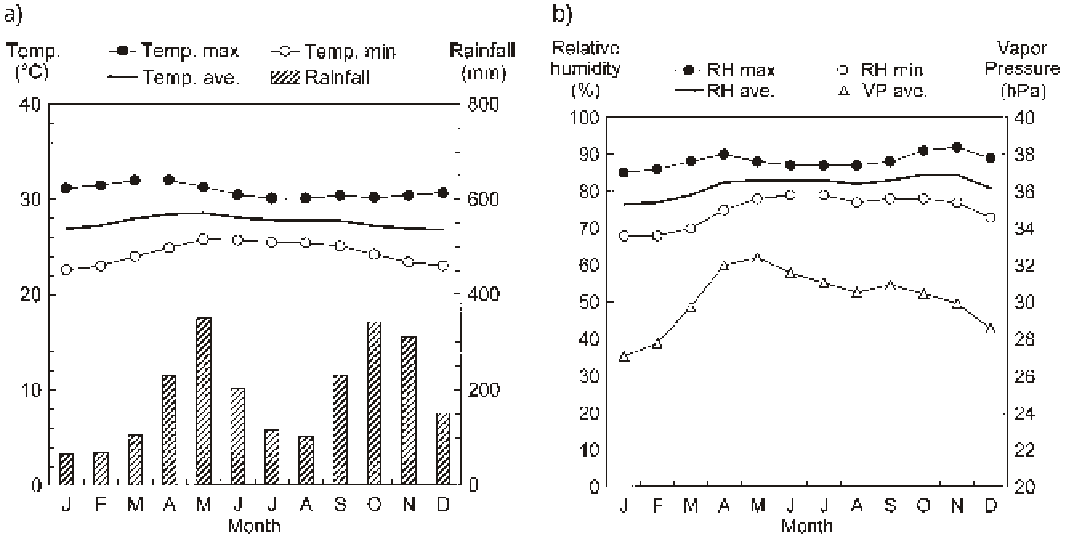


Fig. 3 (a) Monthly mean temperature (maximum, average and minimum) and rainfall. (b) Monthly mean relative humidity (maximum, average and minimum) and vapour pressure. Values based on measurements by Sri Lankan Department of Meteorology for Colombo city weather Stn, 1970–2004. Temp.: temperature; max: maximum; min: minimum; ave.: average (i.e. mean); RH: relative humidity; VP: vapour pressure.

graveled road, ground surface materials consisted of asphalted roads and concrete sidewalks. Building facades generally consisted of plastered bricks or concrete blocks. However, urban geometry and distance to the sea varied (Table 2).

3.2 Field measurements

Field measurements were carried out during the period of April 30 to May 16, 2003. The measurements were taken during the inter-monsoon period, which is characterized by relatively high temperatures and humidity (Fig. 3) as well as low wind speeds. During the measurement period, the average diurnal temperature and relative humidity measured at the Colombo city weather station varied between 26 and 30°C and 75 and 90%, respectively. The total rainfall was 292 mm. These values are very close to the average values for May, thus the weather during the measurement period was representative of the season.

3.2.1 Fixed stations

Air temperature and relative humidity within the street canyons were measured continuously. Air temperature, relative humidity and global solar radiation above roof level were also recorded at the UoM site. Fig. 2 shows the positioning of the measurement equipment within the urban canyons. The rural measurements were made in a clearing within a rubber plantation with few built-up areas in the vicinity. The measured parameters and the instruments used are given in Table 3. All the temperature and humidity probes were shielded with white plastic radiation screens. The instruments were cali-

Table 3 Measured parameters and instrumentation; see Fig. 2 for instrument positions.

Site	Measurement	Parameter	Instrument	Sampling interval
All	Continuous	Air temperature and relative humidity	Gemini Tiny Tag Plus	5 min, averaged to 1 h means
	Instantaneous [a]	Air temperature and relative humidity	Rotronic OP100A	
		Wind speed	Swema SWA03 (hot wire anemometer)	1 s, averaged to 5 min means
		Surface temperature	FSI Thermopoint 62	
UoM [b]	Continuous	Air temperature and relative humidity	Vaisala 50Y	1 h
	Continuous	Global radiation	Skye 1110 pyranometer	1 h

a Measurement period April 30 to May 8, 2003;
b additional measurements.

brated in climate chambers before the commencement of the study and they were calibrated against each other at the end of the measurement period (May 13 to 16, 2003) at the Nugegoda (NUG) site.

Following Oke (2004) temperature and humidity probes should be partitioned as close to pedestrian height as possible and sufficiently away from vertical surfaces. However, this was not possible, for practical (vehicle and pedestrian traffic) and security reasons (risk of theft). Thus, the actual positions in some cases were not ideal (see Fig. 2). However, air temperature differences within an urban canyon are relatively small, except near the canyon surfaces (e.g. Nakamura & Oke 1988). The probes were located at least 1 m from the facades at all the sites. In order to complement the continuous measurements, instantaneous measurements of air temperature and relative humidity were taken at pedestrian level at each site during the first week of the measurement period (the positioning of the probes is shown in Fig. 2). The difference between the fixed and the instantaneous measurements was within ±1 K at all sites including the Pettah (DMP) site, where the logger had to be placed above a lawn in a nearby courtyard (see Fig. 2) where the H/W ratio differed from the street.

Moreover, instantaneous measurements of surface temperatures and wind speed were taken at pedestrian level at each site. The temperatures of the pavements, street and adjacent facades were measured with an infrared thermometer. The wind speed was measured with a directionally independent wind sensor. The instantaneous measurements were taken between April 30 and May 8, 2003 primarily in the morning and in the afternoon.

3.2.2 Reference data

In addition to the fixed stations, official weather data were collected from 3 first-order weather stations maintained by the Sri Lankan Department of Meteorology: Colombo city station, Ratmalana Domestic Airport and Katunayake International Airport, see Table 4 and Fig. 1. The first is located in a residential district within the city limits. The airports, Ratmalana just south of the city and Katunayake some 25 km north of downtown Colombo, are representative of the suburban conditions of the CMR. Data from these synoptic stations were made

Table 4 Official weather data obtained from weather stations Colombo city, Ratmalana, Katunayake. Radiation only measured at Colombo city; wind speed and direction measured at Colombo city and Katunayake.

Parameter	*Measuring height (m)*	*Sampling interval (h)*
Air temperature	1.5	1
Relative humidity	1.5	1
Rainfall		1
Cloud cover		3
Global radiation		1
Wind	4	3

available during the measurement/ calibration period (April 30 to May 16, 2003).

4 Results and discussion

4.1 Classification of days

The measurement period included weather conditions ranging from fairly clear days to overcast days, sometimes with rainfall. In order to categorize the measurement period into synoptic weather types, official weather data from the Colombo city station was used. Cloud cover and global radiation data were used to categorize the measurement period into clear, partly cloudy and overcast days and nights. As expected, the cloud cover was extensive during the whole measurement period and there were no really clear days according to standard definitions (less than 2 octas cloud cover, see e.g. Jonsson 2005). In this study, the definition of ‘clear’ was <5 octas, ‘partly cloudy’ 5 to 7 octas and ‘overcast’ >7 octas. These groups corresponded to the following daily global solar radiation ranges: >5000 Wh m^{-2}, 2000 to 5000 Wh m^{-2} and <2000 Wh m^{-2} respectively. Using this definition, 6 days and 5 nights were categorized as ‘clear’, 6 days and 6 nights were ‘partly cloudy’ and 5 days and 6 nights were ‘overcast’. During the measurement period, sunrise was around 06:25 h, solar transit at 12:37 h and sunset around 18:50 h local standard time (LST). As such, 07:00 to 19:00 h LST was classified as ‘day’ and 20:00 to 06:00 h LST as ‘night’. The classification of days together with rainfall events is shown in Table 5.

4.2. Air temperature

The urban–rural air temperature differences during the measurement period were significant. Under ‘clear’ conditions, differences were slightly greater by day than by night. The intra-urban differences were much larger during the day than at night.

4.2.1 Daytime temperatures at the fixed stations

During clear and partly cloudy days, both heat and cool islands were observed at the urban sites. On clear days, the intra-urban differences reached 7 K and most of the urban sites were cooler than the

Table 5 Weather types and rainfall at Colombo. C = 'clear', PC = 'partly cloudy', OC = 'overcast'. Only rainfall events above 5 mm have been included. Note that the night of April 30 means the night between April 30 and May 1. Rainfall data (mm; duration in h) is from Colombo city weather station.

	Day			Night		
	Sky	Rainfall		Sky	Rainfall	
Date		(mm)	(h)		(mm)	(h)
Apr 30	PC	6	5	OC		
May 1	C			C		
May 2	C			PC		
May 3	C			C	5	1
May 4	C			PC	17	4
May 5	PC			C		
May 6	OC	83	8	PC		
May 7	PC	9	1	OC		
May 8	C			C		
May 9	PC			PC		
May 10	OC	36	6	PC		
May 11	OC	42	7	OC		
May 12	OC			OC	55	9
May 13	OC	10	3	OC	12	3
May 14	C			OC		
May 15	PC			C		
May 16	PC			PC		

rural station (Fig. 4). Such a cool island phenomenon has been noted in several tropical cities (e.g. Nichol 1994, 1996a,b, Jonsson 2005). In the case of Colombo, the reason for the cool islands is likely to be a combination of shading by buildings and sea breeze cooling. Moreover, the urban–rural and intra-urban differences were significant on partly cloudy days (Fig. 5).

The effect of urban morphology is illustrated by the tendency of the maximum temperatures (defined in this study as the temperature at 14:00 h LST) to decrease with increasing H/W ratio. Fig. 6 shows this relationship for clear days, but the trend also exists to a lesser degree on partly cloudy days. The warmest site, NUG, has the lowest H/W ratio, while the coolest sites have higher H/W ratios. A probable reason is that less solar radiation is absorbed at street level for larger H/W ratios. The results of this study agree with Ahmed (1994) who found a similar trend in Dhaka, Bangladesh during the hot-humid summer. Studies in hot-dry climates also show the same trend, e.g. Bourbia & Awbi (2004) and Johansson (in press).

The clearest evidence of the sea breeze effect is the difference between the BoC site and the GRB and DMP sites. All 3 sites are roughly equidistant from the sea, but GRB and DMP are much warmer. The reason is likely to be the blocking of the sea breeze by buildings. The sea breeze is also a contributing factor to the difference between the cool BoC site and the warmest site, NUG, which is about 4 km inland. Evidence of the sea breeze effect can also be found at the UoM site where the temperature at roof level, which the

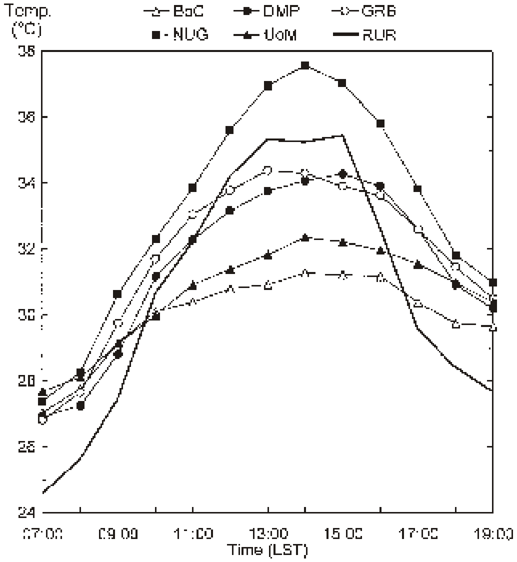


Fig. 4 *Average temperatures of the fixed urban canyon stations on 'clear' days (5 days). RUR: rural station. See Fig. 2 for further abbreviations.*

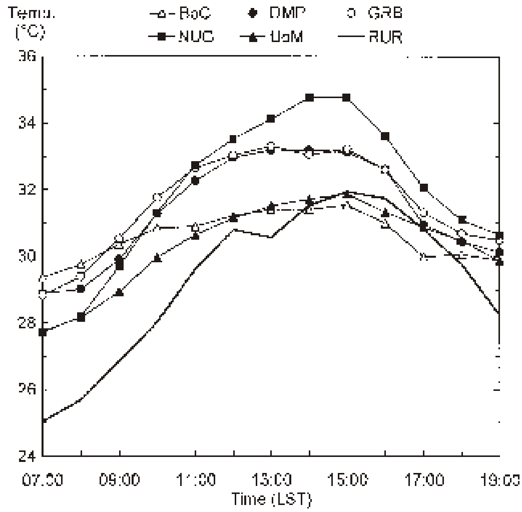


Fig. 5 *Average temperatures of the fixed urban canyon stations on 'partly cloudy' days (4 days). RUR: rural station. See Fig. 2 for further abbreviations.*

sea breeze is probably able to reach, is lower than at street level. It is not known how deep into the city the sea breeze penetrates, but the results indicate that there is little sea breeze penetration at street level, due to the presence of dense development. Nieuwolt (1966) had a similar finding in Singapore. The results of this study agree with the findings of Jonsson (2005) in hot-humid Dar es Salaam, Tanzania, where the sea breeze creates a daytime cool island during the inter-monsoon period (the period when the sea breeze effect was most profound). The effect of sea breeze on the city climate was also noted by Saaroni et al. (2000) in Tel-Aviv, Israel. Places close to the sea, or where the urban morphology allowed the sea breeze to penetrate, were cooler than the rest of that city. As the H/W ratio as well as the distance and openness to the sea differ between the sites, it was not possible to estimate the relative effect of each factor on the cool island.

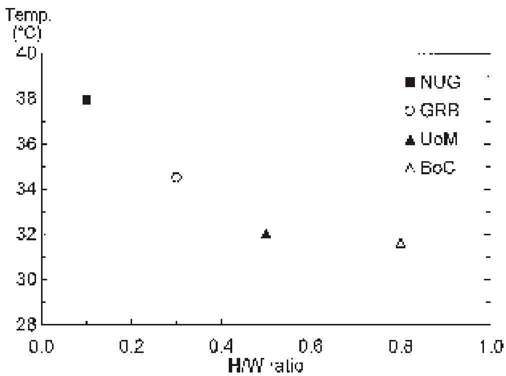


Fig. 6
Relationship between average daily maximum temperatures (at 14:00 h LST) and the H/W ratio on clear days (5 days). See Fig. 2 for abbreviations. DMP site not shown because H/W ratio of courtyard is not known.

The ground cover may also influence intra-urban differences. The only site where permeable ground exists (the graveled road at the UoM site) is among the coolest by day; the other sites all have ground cover of impervious, dense materials such as concrete and asphalt.

The temperature differences between the fixed stations were negligible on overcast days. This is to be expected since solar radiation is limited and the sea breeze is weak. During rainfall caused by afternoon thunderstorms, the temperature could drop drastically by 8 to 9 K. This phenomenon, which is mainly due to downdraft of cool air from high altitudes was found by Nieuwolt (1966) in Singapore.

4.2.2 Nocturnal UHIs at the fixed stations

A small, but distinct, UHI developed during clear and partly cloudy nights. Fig. 7 shows the nocturnal UHIs for 'clear' nights. The magnitude, about 3 K, is smaller than normally found in mid-latitude cities for the same city size and sky-view factor (SVF; the average SVF for the urban sites was 0.5), but is similar to observations in East Asian cities (Oke et al. 1991). The results also agree with results from other hot-humid, coastal cities such as Singapore (Tso 1996) and Dar es Salaam (Jonsson 2005). The probable reasons for the small UHI are: high rainfall (which leads to high soil moisture at the rural site), high humidity in the air and high cloud cover (both of which cause high sky emissivity) (see e.g. Oke et al. 1991).

As expected, there is a general tendency of the UHI effect to diminish with increased cloud cover, although this relationship was not always clear. Variations in wind speed did not seem to influence the magnitude of UHI. However, it must be noted that the measured wind speeds were very small, especially within built-up areas (in general <2 m s^{-1}, see below).

As can be seen in Fig. 7, there were small differences in UHI intensity between the urban sites. No clear relationship between urban geometry, expressed either as H/W ratio or SVF, and UHI could be found, especially in the evening soon after sunset. Instead, 3 of the sites had the highest UHI intensity at the end of the night just before sunrise, and at this time (06:00 h LST) there was a tendency for the UHI to increase with decreasing SVF. However, at the other sites, NUG and GRB, the maximum UHI was just after sunset, especially

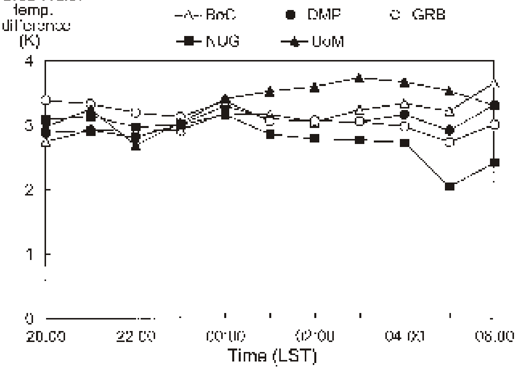


Fig. 7. Average urban-rural temperature differences between fixed stations on 'clear' nights (4 nights). See Fig. 2 for abbreviations.

following clear days with high solar radiation. The reason could be that these sites, which have a low H/W ratio and ground covers of dense, dark surface materials, absorb and store high amounts of heat during the day which is then released after sunset. The degree of intra-urban variation diminished with increased cloud cover, overcast conditions virtually wiping out the differences.

4.3 Solar radiation and surface temperatures

The maximum global solar radiation for 'clear' sky conditions – the instantaneous value at 13:00 h LST – reached 900 W m^{-2}. On overcast days, the maximum was only 400 to 500 W m^{-2}. Only small variations were found between the official values of the Colombo city station and the UoM site, where the global radiation was measured.

The surface temperatures of facades, pavements and streets varied considerably, depending on whether surfaces were exposed to direct solar radiation or not. Under clear sky conditions, dark (i.e. low albedo) horizontal surfaces such as concrete paving and asphalt had temperatures between 50 and 60°C in the early afternoon. The difference between nearby sunlit and shaded spots was between 10 and 20 K. Facades were colder than horizontal surfaces in general, especially around noon when differences reached 10 to 20 K. The reason was the smaller angle of incidence resulting in lower solar radiation flux density, but the fact that some facades had lighter colors than the streets and sidewalks must also be noted. Even so, the facades were 5 to 15 K warmer than the air temperature during sunny conditions. These findings agree with Nakamura & Oke (1988), Nichol (1996a), Pearlmutter et al. (1999) and Ali-Toudert et al. (2005).

The higher surface temperatures have implications on human comfort in urban areas. Johansson & Emmanuel (in press) show that the mean radiant temperature of a person on the sunny side of a street canyon will be very high and consequently the thermal comfort of this person will be very poor.

4.4 Humidity

The relative humidity (RH) varied between sites, but was on average around 75% during the day and around 90% at night. However, the RH on clear days dropped to 55% at the warmest sites (Fig. 8). The average vapour pressure (VP) calculated according to DIN 4108 (DIN 1981) for the Colombo city station was 32 hPa during the measurement period. Fig. 9 shows the average VP of the urban sites compared with the rural site for clear and partly cloudy days. There was evidence of urban moisture excess (UME) during the night. However, the rural VP rose sharply whereas the urban increase was moderate shortly after sunrise, when the convection process started. The latter situation is likely to be due to less evapotranspiration and lower convection within the urban areas (Oke 1987, Mayer et al. 2003). The rural VP decreased in the afternoon, but the urban VP remained almost constant due to decreased evaporation. This is most likely the result of a low ventilation rate within the urban canyons (Oke 1987). Other studies have also found a nocturnal UME with an

Fig. 8
Average relative humidity on 'clear' days (5 days). RUR: rural station. See Fig. 2 for further abbreviations.

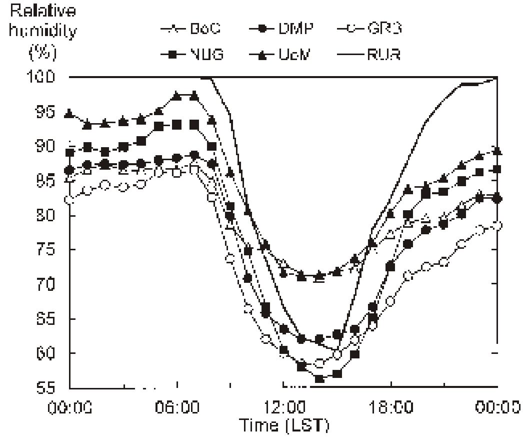
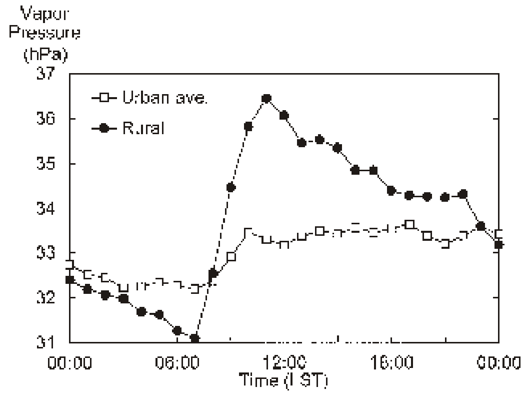


Fig. 9
Average vapour pressure for 'clear' and 'partly cloudy' days (9 days).



urban-rural VP difference (Jáuregui & Tejeda 1997, Holmer & Eliasson 1999, Mayer et al. 2003). Although VP was lower in urban than in rural areas by day, the humidity levels in this study are sufficiently high to have a negative impact on thermal comfort, as the evaporative cooling potential of the human body decreases at high humidity (Givoni 1998).

4.5 Wind

Wind data reported from the official weather stations showed low wind speeds – on average <2 m s^{-1} at the city station – and varying wind directions during the first 2 wk of the measurement period. This was followed by higher wind speeds, more or less consistently from the SW, at the end of the period. Thus, the measurement campaign seems to have covered the last 2 wk of the inter-monsoon period.

The wind roses at 15:00 h and 00:00 h LST for the first 2 wk of the measurement period are shown in Fig. 10. Although the Colombo city station is situated some 2 km inland, there is a SW afternoon sea breeze. At night, however, wind speeds are very low and no prevailing direction can be discerned.

A limited number of instantaneous measurements indicates that wind speeds are higher in shallow canyons (NUG, GRB) and at the

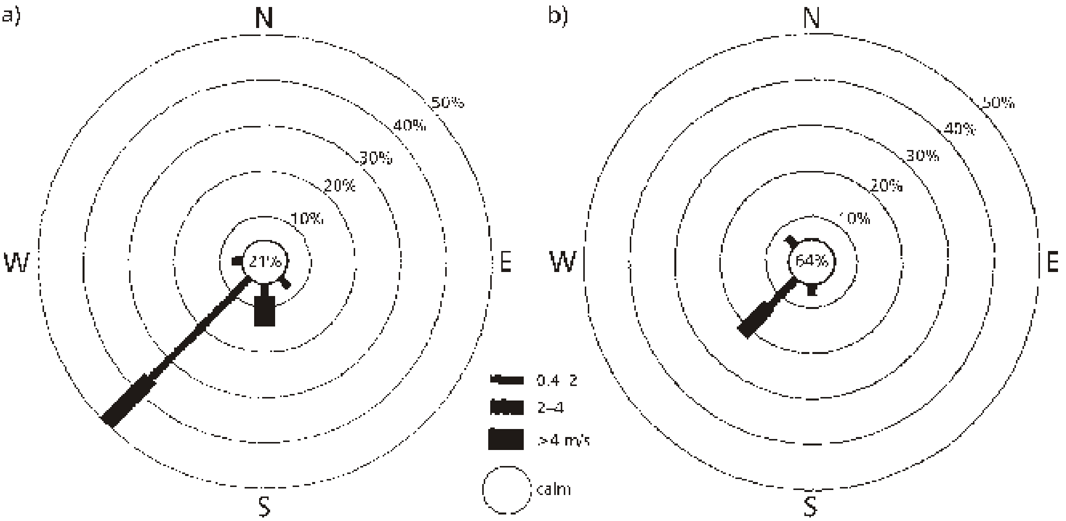


Fig. 10 Wind roses, based on 3-hourly observations, at (A) 15:00 h and (B) 00:00 h LST at the Colombo city weather station for the first 2 wk of measurement period (April 30 to May 13, 2003).

site open to the sea (BoC) than in the deeper canyons (DMP, UoM). The wind speeds at the BoC site were higher than the centrally situated Colombo city station, whereas wind speeds at the deeper canyons of DMP and UoM were lower.

5 Conclusions

The microclimate was measured at 5 urban sites in Colombo, Sri Lanka and at a nearby rural site. The measurements were carried out during the inter-monsoon period in May 2003, when temperature and humidity are at their peak and wind speeds are low. This period is also characterized by high rainfall and a high degree of cloud coverage.

The temperature differences between the urban sites reached 7 K on clear days in spite of the relatively wet period of measurement. Urban morphology had a significant impact on daytime air temperatures; the maximum daily temperature decreased with increasing H/W ratio. There was also evidence of a sea breeze effect; sites open to the sea were significantly cooler than other urban sites. In contrast to the daytime variations, only small intra-urban temperature differences were found at night. It is likely that both the intra-urban and urban–rural differences will be bigger during drier seasons.

The solar radiation was intense on clear days; consequently, sunlit surfaces became very hot, up to 20 K above air temperature. Wind speeds were low in general, but tended to decrease with increasing H/W ratio.

The urban planning and design implications of these findings could contribute to the development of climate-sensitive urban design guidelines on building morphology, street layout and landscape control in Colombo and other cities with similar climate. This study showed that

- The use of high H/W ratios in urban design may be favorable, as this leads to lower daytime air temperatures and more shade at street level.
- Sea breeze penetration into the city should be facilitated by opening up the coastal strip. Currently, medium-rise buildings act as a barrier along much of the coast and intersections consist mainly of narrow streets.
- Horizontal shading is necessary to provide shade to people and urban surfaces around solar noon. This could be achieved by planting shade trees and building pedestrian arcades.

Further studies are needed to develop adaptation strategies that could improve the microclimate at street level in different parts of the city. These could include detailed microclimatic measurements combined with questionnaire surveys to explore comfort preferences of the local population. There is also a need for an evaluation of different climate-sensitive design concepts both by measurements and by computer simulations. Additionally, studies are needed to explore different ways to create shade in the urban environment without reducing air movement. A variation in building height is likely to be beneficial, since this stimulates air movement.

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Paper III

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The influence of urban design on outdoor thermal comfort in the hot, humid city of Colombo, Sri Lanka

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Abstract

The outdoor environment is deteriorating in many tropical cities due to rapid urbanization. This leads to a number of problems related to health and well-being of humans and also negatively affects social and commercial outdoor activities. The creation of thermally comfortable microclimates in urban environments is therefore very important. This paper discusses the influence of street canyon geometry on outdoor thermal comfort in Colombo, Sri Lanka. Five sites with different urban geometry, ground cover and distance from the sea were studied during the warmest season. The environmental parameters affecting thermal comfort, viz. air temperature, humidity, wind speed and solar radiation, were measured and the thermal comfort was estimated by calculating the physiologically equivalent temperature (PET). The thermal comfort is far above the assumed comfort zone due to the combination of intense solar radiation, high temperatures and low wind speeds, especially on clear days. The worst conditions were found in wide streets with low-rise buildings and no shade trees. The most comfortable conditions were found in narrow streets with tall buildings, especially if shade trees were present, as well as in areas near the coast, where the sea breeze had a positive effect. In order to improve the outdoor comfort in Colombo it is suggested to allow a more compact urban form with deeper street canyons, and to provide additional shade through the use of trees, covered walkways, pedestrian arcades, etc. The opening up of the city's coastal strip would allow the sea breeze to penetrate further into the city.

Keywords: Outdoor thermal comfort, Urban microclimate, Urban design, Hot humid climate, Colombo.

Introduction

There are several reasons for creating a more comfortable outdoor environment in cities. The importance of making urban space attractive and accessible has increased in recent years, as it has social, cultural and economic benefits. The use of urban space is more likely to increase if the outdoor environment is thermally comfortable. Thermal comfort is also important for the well-being of people. This is especially important in warm countries as the risk of heat related illness increases with higher temperatures. Furthermore, outdoor activities are possible for most of the year in warm countries, where the appropriate design of outdoor spaces increases outdoor liveability (see Correa 1989). A thermally comfortable outdoor environment will also have a positive influence on the indoor climate, which will lead to lower energy use for space conditioning.

Many tropical cities are currently subjected to rapid population growth – a process in which land use, urban form and ground cover are all changing. The urbanization is very fast and design issues related to urban climate and outdoor comfort are normally neglected. In tropical cities this is likely to increase the levels of discomfort. Studies in Pune, India (Deosthali 1999), and Colombo, Sri Lanka (Emmanuel 2005b) show that outdoor thermal comfort, expressed in the temperature-humidity index (Pune, Colombo) as well as the relative strain index (Colombo), has decreased during the recent decades as the cities have grown. There has also been a change of lifestyle among urban dwellers, especially in the medium and high-income groups, who nowadays tend to spend more time indoors (Ahmed 2003). These changes are likely to contribute to an increased use of air conditioning and thus higher energy use. The use of air conditioning may in fact further increase outdoor temperatures as the excess heat is emitted to the urban air and more cooling will be needed as a result of the vicious circle created in this situation (de Schiller and Evans 1998; Baker et al. 2002). There is, thus, an urgent need to improve the current situation and to allow for the creation of improved urban climate conditions within the ongoing urbanization.

Urban form has a significant influence on the urban climate and, consequently, on outdoor thermal comfort at street level. The nocturnal urban heat island has been shown to be directly linked to urban geometry, often defined as the height to width (H/W) ratio of urban street canyons: the higher the H/W ratio, the bigger the nocturnal heat island (Oke et al. 1991; Arnfield 2003). However, there is also a link between urban geometry and air temperature during the day. In the hot humid summer of Dhaka, Bangladesh, Ahmed (1994) found that the maximum air temperature decreased with increased H/W ratios. Similarly, in the hot, but dry, climate of Fez, Morocco, Johansson (2006) found that a very deep street canyon had a considerably lower air temperature than a shallow street canyon. In hot, humid Colombo, Sri Lanka, Emmanuel and Johansson (2006) found intra-urban differences in maximum daily temperatures of up to 7 K between sites of different H/W ratios.

The studies on outdoor thermal comfort in hot, humid climates are few. However, comfort studies of climates with a warm summer season have recently been presented (Ahmed 2003; Nikolopoulou et al. 2003; Spagnolo and de Dear 2003). These studies, which have been based on combined measurements and subjective thermal comfort assessment, have shown that there is a discrepancy between calculated and subjectively perceived thermal comfort. People in the outdoors seem to accept much more difficult climate conditions than when indoors. However, the main aim of these comfort studies has been the perception of outdoor thermal comfort and not how urban design influences thermal comfort.

There is a need to understand the relationship between urban design and outdoor thermal comfort in hot, humid climates in order to develop climate-conscious urban design guidelines. The aim of this paper is to show how thermal comfort is affected by factors such as the H/W ratio of the street canyon, the orientation of the street and the ground cover, as well as the distance from the sea. This is done by comparing five urban sites in the hot, humid city of Colombo, Sri Lanka. The calculation of thermal comfort is based on field measurements of air and surface temperatures, solar radiation, humidity and wind speed.

Materials and methods

The city of Colombo

The city of Colombo (6°54'N, 79°52'E) is located on Sri Lanka's west coast (Fig. 1). The city had a population of approximately 0.65 million in 2001 and is in the centre of the almost entirely urbanized Co-

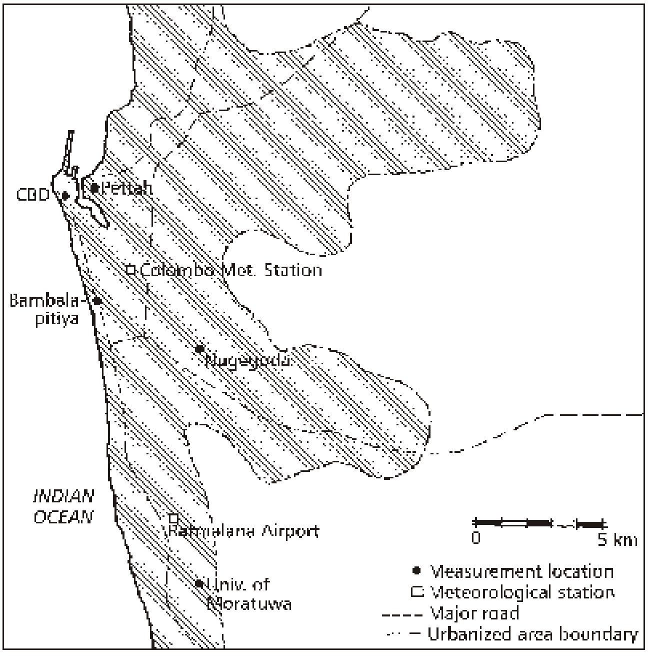

Fig. 1
The city of Colombo and its surroundings showing the five urban measurement sites (CBD = central business district).

lombo Metropolitan Region (CMR). The CMR's population in 2001 was 5.3 million and the region extends about 100 km in the north–south direction and 40 km in the east–west direction.

Generally speaking, Colombo is a low density city with a lot of greenery and low-rise buildings, but it has heavy concentrations of medium-rise buildings along the major traffic arteries. On account of the natural limits on the west (Indian Ocean) and the east (extensive marshlands), the city has generally grown in a north-south direction along the national highways. The combination of fairly wide streets, regulatory set backs and low-rise buildings, results in street canyons with low height to width (H/W) ratios. Exceptions are the central business district (the old colonial "Fort" area), the old commercial quarters (Pettah) and the main traffic arteries that generally run in a north–south direction. Fort is characterized by high-rise buildings and some very tall, tower buildings while Pettah is dominated by medium rise buildings (3–4 storeys) and narrow streets. The main transport axis in the city, Galle Road, which runs in a north–south direction parallel to the coast at a distance of some 200 m is bordered by medium-rise buildings along a large part of its extension within the city. Since its intersections consist mainly of narrow streets, the row of buildings along Galle Road is effectively blocking the sea breeze.

The ground cover and amount of vegetation vary greatly between neighbourhoods: from an almost complete canopy cover in exclusive residential neighbourhoods to paved/asphalted streets with few trees. The outskirts of Colombo could be characterized as semi-urban; buildings are mainly positioned along the roads and the areas in between consist of agricultural land, including paddy and cash crop fields, as well as marsh, open areas and water bodies. The city has relatively few parks, few outdoor restaurants and cafés and few places for outdoor recreation (one exception being the Galle Face Green by the coast, which due to its openness takes full advantage of the sea breeze).

The climate of Colombo[1]

Colombo is a lowland region with a typically hot humid, tropical climate that is affected by the seasonal wind reversal of the Asiatic monsoon, which blows from the southwest from late May to late September and from the northeast from late November to mid-February. The temperature and humidity are high throughout the year creating an uncomfortable thermal environment, which, however, would be worse without the afternoon sea breeze. The inter-monsoon period between March and May is the most uncomfortable; temperatures are at their peak, the relative humidity is high and wind speeds low because of the formation of a convergence zone. During this period, the minimum and maximum air temperatures are between about 25 and 32°C, respectively, and the average relative humidity is around 85%. In December and January, which are

1 Based on measurements from Colombo Meteorological Station 1970–2004. The station is located in a low-density, fashionable residential neighbourhood with significant green cover.

the least uncomfortable months, the air temperature varies between 23 and 31°C and the average relative humidity is about 80%. Rainfall is high throughout the year, with abundant rainfall during April to June and October to November.

Solar radiation is intense under clear sky conditions. However, there is often a high probability of cloud development, especially during the afternoon. At this time of the day thunderstorms are frequent. The number of hours of sunshine is between 8 and 9 hours from February to March and between 6.5 and 7 hours for the remainder of the year. Being close to the equator, the solar elevation is very high throughout the year except in the mornings and the evenings. From October to March the sun is to the south with the lowest elevations at solar noon of about 60° in December. In August and April the sun is virtually in its zenith at noon. From May to July the sun is slightly to the north.

Choice of measurement sites

Five measurement sites were chosen within the city of Colombo and its suburbs (Fig. 1). The urban sites were chosen in order to represent different neighbourhoods, ranging from dispersed, low-rise suburban areas to densely-populated central areas as well as the high-rise business district. The sites were characterized by the differences in the H/W ratio of street canyons, orientation, surface material properties, vegetation and proximity to the coast. The neighbourhoods of the selected sites are described in Table 1. The distribution of ground cover shown in this table is taken from Emmanuel and Johansson (2006). A more detailed description of the measurement

Table 1 Land use and ground cover of the measurement sites and their surroundings.

Site	Key	City district	General description	Land use	Buildings	Ground cover (%)[a]		
						Built-up	Roads and paving	Green
Bank of Ceylon	BoC	Central business district (Fort)	Downtown location, the central business district.Close to sea-shore, some trees	Commercial/ office high towers	High-rise, some very	40	55	5
Dutch-period Museum, Prince Street	DMP	Pettah	Downtown location, the old commercial quarters, just east of Fort. Away from shore, almost devoid of vegetation	Commercial/ residential	Medium rise (3–4 storeys)	60	40	0
Galle Road	GRB	Bambalapitiya	Commercial sector south of Fort, some trees. Close to sea shore, but buildings act as a barrier to sea breeze	Commercial/ office	Low to medium rise (1–4 storeys)	35	55	10
Pagoda Road	NUG	Nugegoda	Mixed-residential sector south-east of the city centre. Away from the sea	Residential	Low rise	30	50	20
University of Moratuwa	UoM	Moratuwa	Low-density, suburban location south of the city. Away from the sea	Institutional	Medium rise	20	20	60

a Calculated for a radius of 200 m around each site.

Table 2 Description of the street canyons where the measurements were performed (for site keys, see Table 1)

Site	*Type of street*	*H/W* [a]	*SVF* [b]	*Orientation*	*Vehicle traffic*	*Ground cover*	*Dist. from sea* [d] *(km)*
BoC	Commercial, medium sized street	0.8	0.49	E/W	Medium	Concrete pavements, asphalted road, some green	0.2
DMP	Commercial, narrow street	1.2	0.31	ENE/WSW	Low [c]	Concrete pavements, asphalted road, no green cover	0.5
GRB	Commercial, 6-lane highway	0.3	0.65	NNW/SSE	High	Concrete pavements, asphalted road, little green	0.3
NUG	Residential, main road through neighbourhood, medium sized street	0.1	0.75	NNE/SSW	Medium	Asphalted pavements and road, bare ground, little green	4
UoM	Institutional, narrow street	0.5	0.44	E/W	Low	Concrete pavements, gravelled road, some green	3

a Approx. values (average).
b Sky view factor (SVF) calculated by RayMan (Matzarakis et al. 2000) at the centre of the road.
c Restricted vehicular, but lively pedestrian traffic.
d Shortest distance perpendicular to the sea.

sites is given in Table 2 and Figs. 2–6, which show plans and sections.

Meteorological measurements

Air temperature and relative humidity within, or near, the street canyon were measured continuously at each field site. Figs. 2–6 show the positioning of the measurement equipment. The measurements were done with Tinytag Plus miniature loggers (Gemini Data Log-

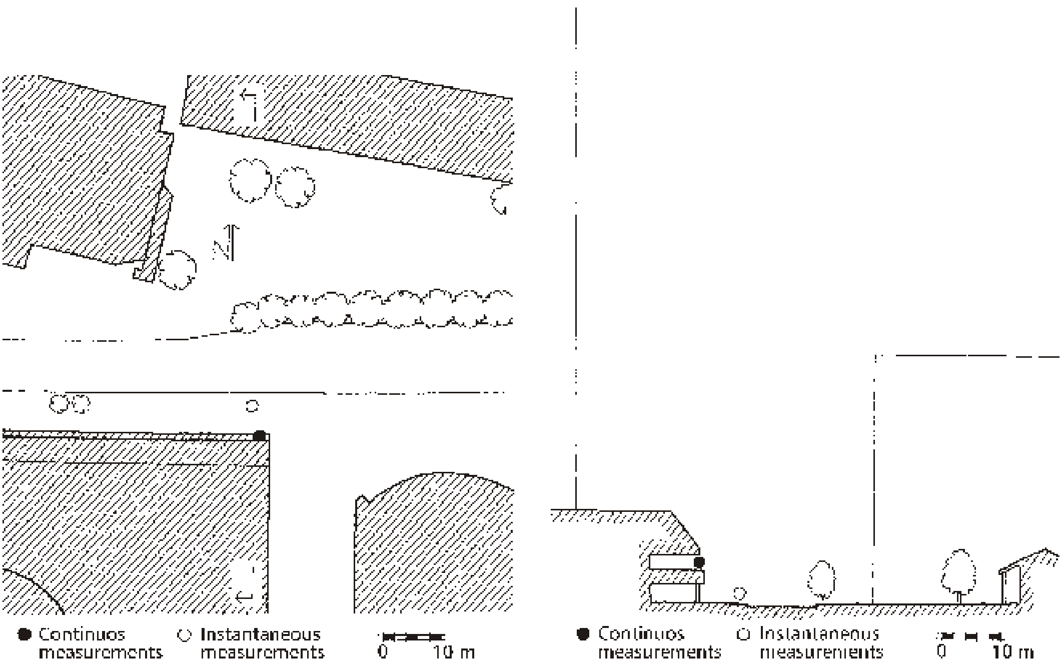

Fig. 2 Plan and section of the Bank of Ceylon site (BoC) in the central business district showing the position of the measurement equipment.

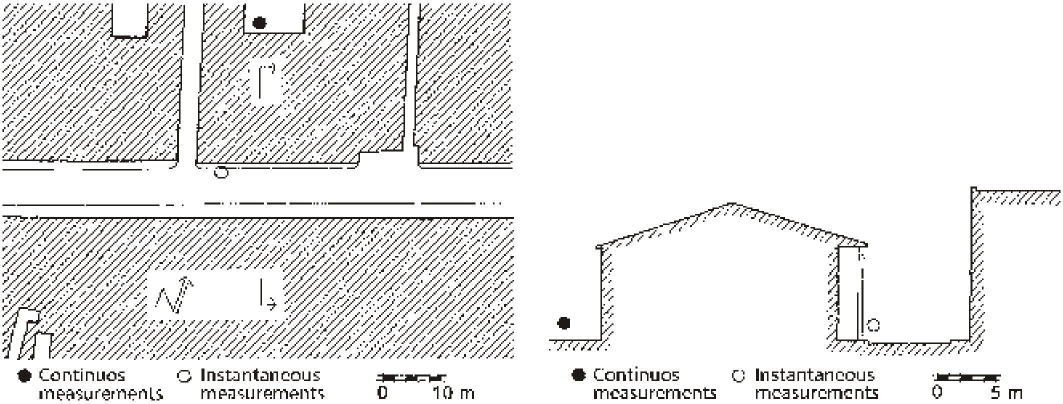

Fig. 3 *Plan and section of the Prince Street (Dutch-period Museum) site in Pettah (DMP) showing the position of the measurement equipment.*

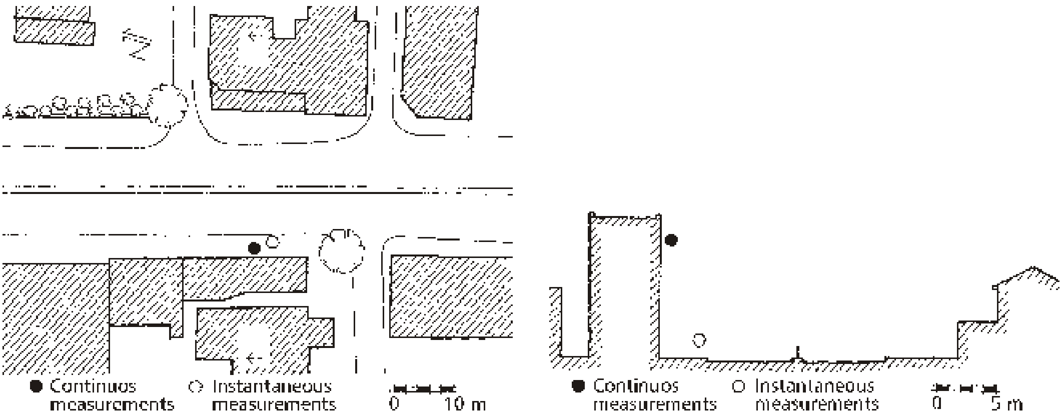

Fig. 4 *Plan and section of the Galle Road site in Bambalapitiya (GRB) showing the position of the measurement equipment.*

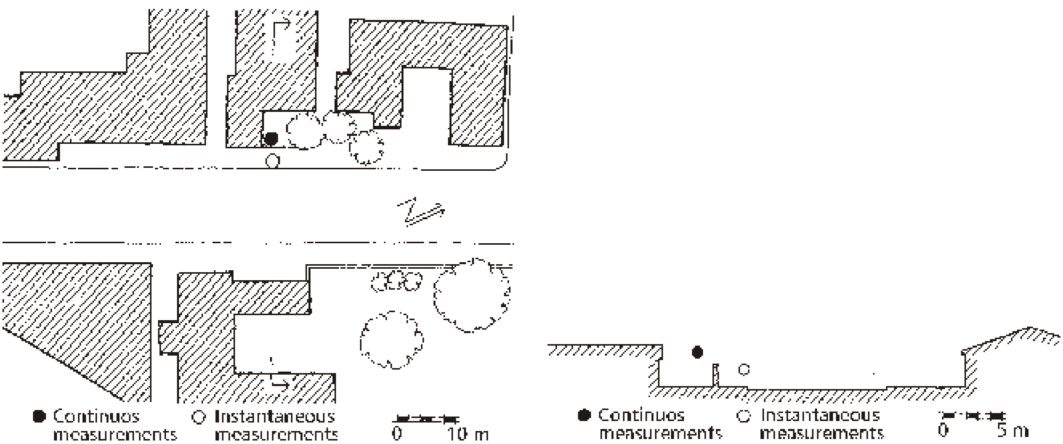

Fig. 5 *Plan and section of the Pagoda Road site in Nugegoda (NUG) showing the position of the measurement equipment.*

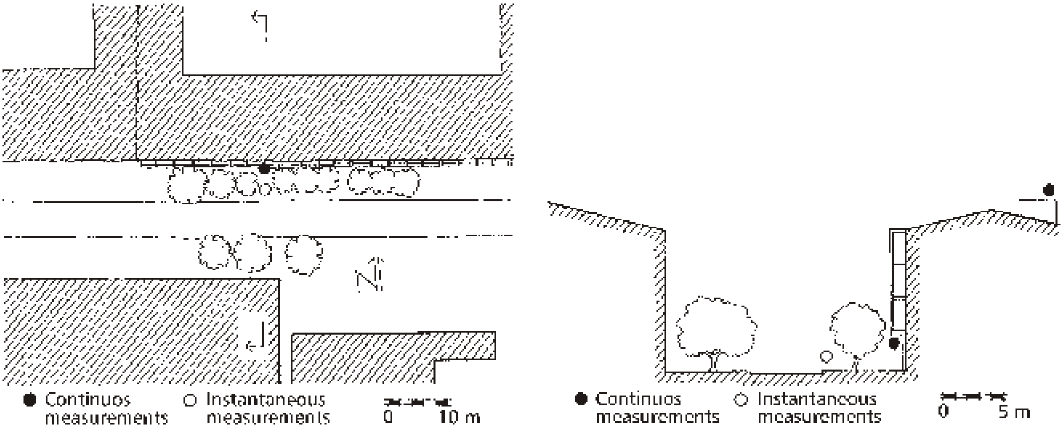

Fig. 6 Plan and section of the University of Moratuwa (UoM) site (School of Architecture) showing the position of the measurement equipment.

gers). These loggers have a temperature accuracy of ±0.5 K (resolution 0.3 K) and relative humidity accuracy of ±3% (resolution 0.5%). Recordings were made every 5 minutes and averaged to 1 hour means. At the University of Moratuwa (UoM) site, air temperature and relative humidity (Vaisala 50Y probe) and global solar radiation (Skye 1110 pyranometer) were also measured above roof level. The probes were connected to a Campbell CR10X logger and recordings were made hourly. The stationary measurements took place between 30th April and 12th May 2003. This period fell within the intermonsoon from April to May, which is characterized by high temperatures, high humidity and low wind speeds. The measurement equipment was calibrated in climate chambers at Lund University before the measurements were taken. Post-measurement calibrations were done at the Nugegoda (NUG) site.

The aim of the data collection regime was to capture the thermal environment experienced by pedestrians by positioning the miniature temperature and humidity loggers as near pedestrian height as possible and sufficiently far away from the façades – as recommended by Oke (2000), in order to avoid the influence of warm surfaces. This was, however, not possible for practical and safety reasons (pedestrian traffic and the risk of thefts) and the actual positions were, in some cases, quite far from ideal (see Figs. 2–6). However, several studies have shown that the air temperature differences within an urban canyon are fairly small except when in close proximity to the canyon surfaces (see e.g. Nakamura and Oke 1988; Santamouris et al. 1999). In the DMP case, the logger had to be placed in an adjacent courtyard with a lawn (see Fig. 3). However, the difference in H/W ratio between the street and the courtyard is small and the instantaneously measured temperature and humidity in the street canyon (see below) differed only slightly from the courtyard values (in general the temperature was within ±1 K and RH within ±5%).

In order to complement the continuous measurements, instantaneous measurements of air and surface temperatures, relative humidity and wind speed were performed at pedestrian level on each site. Air temperature and wind speed were measured with a Swema SWA03 probe, which is a directionally independent wind sensor consisting of a hot wire anemometer and a PT100 sensor to measure temperature. The wind sensor has an accuracy of ±4% up to a wind speed of 3 m/s (above this speed the accuracy is not specified). The temperature sensor has an accuracy of ±0.5 K. Wind speeds were collected as mean values from 5 minute recordings at each site. Relative humidity was measured with a Rotronic OP100A. Surface temperatures were measured with an infrared camera (Thermopoint 62, FSI instruments). The instantaneous measurements took place between 30th April and 8th May 2003.

In addition to the chosen sites, official weather data from three weather stations in the CMR region was used. The Colombo Meteorological Station is centrally situated in Cinnamon Gardens, a neighbourhood that is characterized by a very high level of vegetation. Temperature and humidity measurements take place 2 m above an open lawn, wind is measured at a height of 4 m and global solar radiation is recorded from the roof of a building. The other official stations are airports – the international airport in Katunayake, some 25 km north of Colombo city centre, and the smaller domestic airport in Ratmalana just south of the city, close to the UoM site.

Choice of thermal comfort index

There is a lack of a thermal comfort index that is appropriate in respect of the complex urban outdoor environment (Spagnolo and de Dear 2003; Emmanuel 2005a). Indices designed for outdoors are, with few exceptions, designed to measure thermal stress under extreme outdoor conditions, often related to physical work, e.g. manual labour and military activities (McIntyre 1980; Emmanuel 2005a). In the absence of a suitable outdoor comfort index, recent studies have often used the most common thermal comfort indices developed for indoors, such as the predictive mean vote (PMV), the effective temperature (ET*) and the standard effective temperature (SET*). However, these indices are based on steady-state heat balance equations of the body. This assumption does not hold in the outdoor, where temporal and spatial variations are large. Indices such as OUT–SET* (an outdoor version of SET*, Pickup and de Dear 2000), and the physiologically equivalent temperature (PET, Höppe 1999) are designed for outdoors, but are also based on the heat balance of the human body. Although PMV, ET*, SET* and PET have proved to have limited applicability outdoors (see e.g. Spagnolo and de Dear 2003), they all take into account the four environmental parameters which influence thermal comfort: air temperature, mean radiant temperature, humidity and air movement. PMV and SET* also include clothing insulation and the level of activity.

Since the aim of this study was to compare the thermal comfort of different sites rather than calculating an exact thermal comfort level, the PET index, which has been used in several recent studies (e.g. Matzarakis and Mayer 1997; Spagnolo and de Dear 2003), was chosen. This index does not take clothing or activity into account, but since these values did not vary significantly between the studied sites, an index which included these personal parameters was not necessary. The PET index, which is expressed in °C, was calculated using a software annexed to the VDI guidelines (VDI 1998). The required input data consists of air temperature, mean radiant temperature, humidity and wind speed.

No comfort zone for outdoor tropical conditions has been defined for the PET index. However, based on his field study in Dhaka during the hot humid summer months, Ahmed (2003) derived a comfort zone for subjects in shade with an activity of 1 met (i.e., sedentary) and clothing values varying between 0.35 and 0.5 clo. The comfort zone is a result of subjective comfort votes of some 1500 randomly selected subjects using the Bedford seven-point scale (see e.g. McIntyre 1980). For still air, thermal comfort was found in a temperature range of between 27.5 and 32.5°C; the range of relative humidity was 50–75% at 32.5°C and 50–85% at 27.5°C. Increased airflow extended the upper comfort limits. Assuming that the air and radiant temperatures are equal, Ahmed's comfort zone would correspond to PET values roughly between 27 and 33°C. However, these estimated PET values are very uncertain and the comfort zone found by Ahmed (2003) in Dhaka is not necessarily transferable to Colombo. Nevertheless, the estimated upper thermal comfort limit of PET = 33°C has been used as a reference in this study since no other reference values are available at present.

Calculation of the mean radiant temperature

Among the variables generally associated with thermal comfort, mean radiant temperature (MRT) is the critical difference between indoor and outdoor conditions. In the hot, humid outdoors, MRT is probably the second most important environmental parameter, after air temperature. The MRT is often calculated as the weighted average temperature of surrounding surfaces. It is more complicated to calculate the MRT in an outdoor urban environment than in an indoor one due to factors such as the exposure to solar radiation, the varying shapes and positions of buildings and the presence of objects such as trees, etc.

Ideally, the MRT is calculated from measurements of short-wave and long-wave radiation at pedestrian level as described in e.g. Spagnolo and de Dear (2003) and Ali-Toudert et al. (2005). However, in this study only the global solar radiation was measured and the measurements took place above roof level. Therefore, the software "RayMan" (ver. 1.2, Matzarakis et al. 2000) was used to calculate the MRT. The input data required for RayMan is the geometry of the site (position and shape of surrounding buildings and trees), albedo, global solar radiation measured from the position of the subject (e.g. at 1 m above ground for a standing person) and cloud cover. Based on the input data, RayMan estimates the surface temperatures of the façades, calculates the view-factors for the surrounding surfaces and the sky, and estimates the incoming long-wave radiation from the sky. Finally, MRT is calculated as (VDI 1998):

$$\mathrm{MRT} = \left[\mathrm{MRT}^{*4} + \frac{f_p a_k I_b}{\varepsilon_p \sigma}\right]^{0.25}, \qquad (1)$$

where

$$\mathrm{MRT}^{*} = \left[\frac{1}{\sigma}\sum_{i=1}^{n}\left(\varepsilon_i \sigma T_{si}^4 + \frac{a_k D_i}{\varepsilon_p}\right)F_i\right]^{0.25}, \qquad (2)$$

MRT* = mean radiant temperature from long-wave and diffuse short-wave radiation (not including direct beam radiation) [°C]
f_p = surface projection factor of a standing or walking person
I_b = beam radiation (on a plane perpendicular to the beam) [W/m^2]
a_k = average (short-wave) absorptivity of the human body = 0.7
ε_p = emissivity of the human body = 0.97
σ = 5.67 10-8 W/m^2K^4 (the Stefan-Boltzmann constant)
ε_i = emissivity of the surface
$T_{s,i}$ = surface temperature [K]
D_i = diffuse radiation [W/m^2]
F_i = view-factor of the surface.

According to the authors' knowledge, all of the steps that RayMan uses to calculate MRT have not been presented in detail. This is especially the case with respect to the incoming long-wave radiation from the sky and the surface temperatures. Except for albedo (which is given as a single value), no surface or thermal properties of the façades and trees surrounding the subject are required to perform the calculations. Nevertheless, it is reported that calculated values of MRT have shown good correlation with measured values in some urban environments (Matzarakis et al. 2000).

In order to estimate the solar radiation at street level, the global solar radiation above roof level – measured at the Colombo Met. Station – was first divided into its direct and diffuse components. During fair weather conditions, the diffuse part was assumed to be 20% of the total. During partly cloudy conditions, the diffuse part was assumed to be 60%. The global radiation at street level is then the sum of the direct and the diffuse components, where the diffuse radiation depends on the geometry of the street canyon and decreases with the canyon depth. The approximate global radiation at 1 m height was calculated as:

$$I_g = I_{dir} + SVF \times D_i \qquad (3)$$

where I_g = global solar radiation (W/m^2), I_{dir} = Direct solar radiation (W/m^2), SVF = Sky view factor (at 1 m height), D_i = Diffuse solar radiation (W/m^2). Note that reflections from the façades and the street are not taken into consideration and, consequently, the global radiation received by the subject will be underestimated. During periods of shade $I_{dir} = 0$ and the person receives only diffuse radiation. The SVF at the position of the subject was calculated by the RayMan software.

Results and discussion

Site observations

During daytime on normal weekdays, the most crowded sites were Prince Street, Pettah, which has many shops and markets, and the Bank of Ceylon site in the central business district, whereas the least crowded street was Pagoda Road in the residential district of Nugegoda. The pedestrians observed in the streets were mainly walking by. There were no facilities such as open-air cafés or benches near the measurement sites. The physical activity of the people in the street was that of slow walking or standing, which corresponds to a metabolic rate of about 1.2–2 met according to ASHRAE (1997). Clothing was similar in all places and consisted of light shirts and light, but long, trousers or skirts. Traditional dress was common. The clothing insulation value was estimated from ASHRAE (1997) to 0.4–0.5 clo (although higher for office workers). Compared to the conditions reported by Ahmed (2003), the observed clothing insulation was similar but the metabolic rate was higher. The assumed upper comfort limit might therefore be overestimated.

Measured environmental parameters

The measurement period included a variety of weather conditions ranging from fairly clear days, with intense solar radiation, to overcast days, sometimes with rainfall. Temperature, humidity and solar radiation varied greatly depending on the weather. Therefore, the measurement data was divided into *clear*, *partly cloudy* and *overcast* days and nights. The criteria for clear was cloud cover < 5 octas and

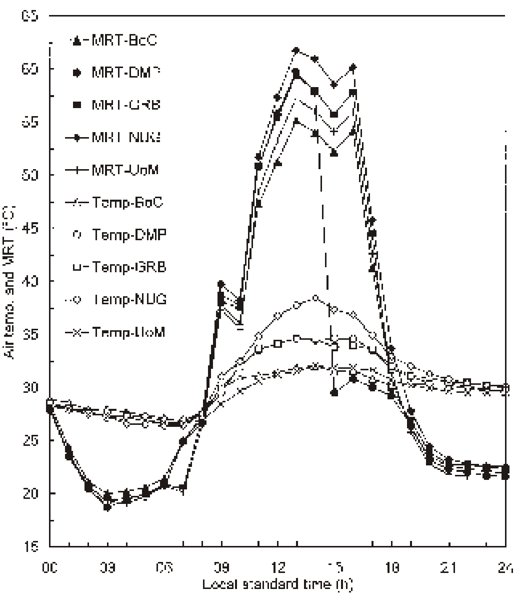

Fig. 7 Measured air temperature and calculated MRT on a clear day (3rd May 2003) for a subject on the sunny side of the street.

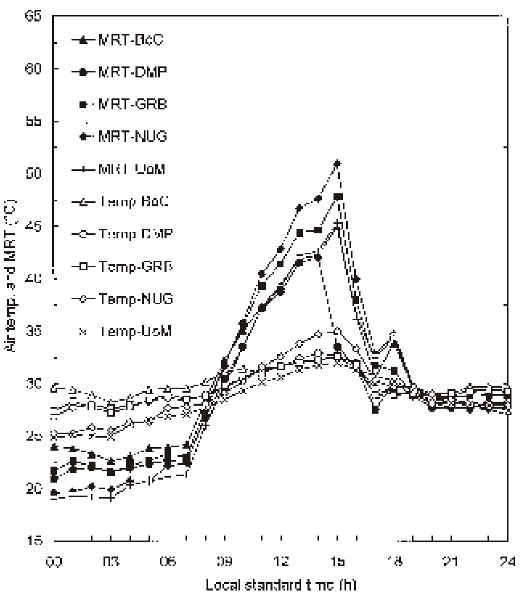

Fig. 8 Measured air temperature and calculated MRT on a partly cloudy day (7th May 2003) for a subject on the sunny side of the street.

Fig. 9
Measured air temperature and calculated MRT on an overcast day (6th May 2003). The drop in temperature starting at around noon is due to rainfall.

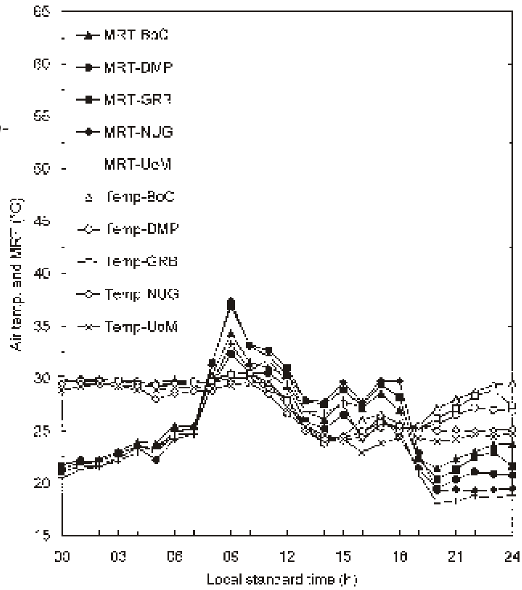

Table 3   Classification of measurement data into clear, partly cloudy and overcast days and nights.

		Night		
		Clear	*Partly Cloudy*	*Overcast*
Day	Clear	May 1,3,8	May 2, 4	
	Partly cloudy	May 5	May 9	Apr. 30, May 7
	Overcast		May 6, 10	May 11

a total daily global radiation of I_g > 5000 Wh/m², for partly cloudy 5–7 octas and I_g = 2000–5000 Wh/m² and for overcast > 7 octas and I_g < 2000 Wh/m². The classification of days is shown in Table 3.

The air temperature on a clear, a partly cloudy and an overcast day are shown in Figs. 7–9. The difference between the sites was bigger in the afternoon than during the night. On clear days, the maximum difference found between sites in the early afternoon was 7 K (see Fig. 7). The lower air temperatures were found at sites, which had high H/W ratios and/or were open to the sea breeze. As expected, the sites with the highest H/W ratios were the warmest at night. The cloudier the sky, the smaller the difference in temperature between the sites, both by day and night. During afternoon thunderstorms, daytime temperatures dropped dramatically (see Fig. 9), which was experienced as a thermal relief.

In general, horizontal surfaces such as streets and pavements were warmer than vertical surfaces. During clear weather, dark horizontal surfaces had temperatures above 50°C during the hours around midday. On such days, temperature differences of up to 20 K were found between sunlit and shaded surfaces within the street canyons.

Average wind speeds between 0.7 and 5.4 m/s were recorded. It should be noted that the number of measurements were few, but

Table 4 Input data for the calculation of the physiological equivalent temperature (PET) for the street canyons described in Table 2 on 3rd May (clear day): air temperature, relative humidity and global radiation.

	Air temperature (°C)					Relative humidity (%)					Global solar radiation[a] (W/m²)				
Hour	BoC	DMP	GRB	NUG	UoM	BoC	DMP	GRB	NUG	UoM	BoC	DMP	GRB	NUG	UoM
1	28.6	28.1	28.1	28.0	28.0	85.5	88.6	82.5	92.5	90.6	0	0	0	0	0
2	27.9	27.8	27.6	27.5	27.5	87.1	88.8	83.0	92.3	90.3	0	0	0	0	0
3	28.0	27.2	27.4	27.3	27.3	85.6	87.5	81.9	92.3	91.4	0	0	0	0	0
4	27.7	27.4	27.3	26.6	26.9	87.2	88.3	83.8	94.4	93.9	0	0	0	0	0
5	27.4	27.2	26.8	26.5	26.9	88.8	89.4	85.8	96.7	94.7	0	0	0	0	0
6	27.1	26.9	26.6	26.4	26.7	90.2	90.3	86.9	96.8	95.7	0	0	0	0	0
7	26.8	26.9	26.6	26.4	26.6	90.1	90.5	87.2	96.4	95.8	80	77	12	85	9
8	27.7	27.4	27.5	27.5	26.9	87.3	88.6	83.3	92.4	95.6	106	102	110	113	106
9	29.9	29.5	29.9	31.0	28.4	79.0	80.7	73.6	80.3	89.6	298	286	309	316	296
10	30.9	32.0	31.9	32.4	29.6	75.1	70.7	66.3	74.1	82.8	267	256	277	284	265
11	31.1	33.5	33.6	34.8	30.6	74.1	65.2	61.2	64.1	76.2	555	532	576	589	551
12	31.4	34.1	34.1	36.7	31.2	72.0	63.6	59.8	57.4	71.9	699	671	725	742	694
13	31.8	34.6	34.6	37.7	31.5	70.2	62.6	58.3	54.4	70.6	758	727	786	805	753
14	32.0	34.4	34.5	38.4	32.0	69.8	61.8	58.6	53.7	69.3	661	634	686	702	657
15	31.5	34.6	33.8	37.3	31.8	71.2	60.7	60.4	55.5	70.8	572	42	593	607	568
16	31.6	34.6	33.9	36.8	31.8	71.0	60.0	60.1	57.7	71.4	558	41	579	593	555
17	30.8	33.5	33.6	34.9	31.6	74.4	64.5	61.6	63.0	74.0	261	19	271	277	259
18	30.2	31.7	32.0	32.9	30.7	78.3	71.9	66.2	70.8	77.7	53	4	8	57	53
19	30.3	31.0	31.1	32.0	30.2	78.0	75.0	69.0	74.7	78.4	2	1	3	3	2
20	30.3	30.4	30.9	31.3	29.9	77.5	75.8	69.7	75.6	79.5	0	0	0	0	0
21	30.2	30.4	30.5	30.8	29.7	77.4	76.1	70.4	77.2	80.4	0	0	0	0	0
22	29.9	30.1	30.5	30.4	29.5	78.8	77.3	71.5	79.5	82.1	0	0	0	0	0
23	29.7	29.8	30.2	30.2	29.5	80.2	78.6	72.9	80.8	83.4	0	0	0	0	0
24	29.6	29.7	30.0	30.2	29.5	82.4	80.6	75.7	82.8	84.6	0	0	0	0	0

a Calculated at 1 m height for an object on the sunny side of the street according to Eq. 3.

they indicated that wind speeds were higher in wide streets and in streets open to the sea (Table 7).

The humidity was generally high – between 70 and 100%. However, on clear days relative humidities dropped to between 55 and 60% in the early afternoon at the warmest sites.

For a more detailed analysis of the climate measurements, see Emmanuel and Johansson (2006).

Calculated thermal comfort

The calculated values of the mean radiant temperature (MRT) for a clear, a partly cloudy and an overcast day are shown in Figs. 7–9 (the input data is given in Tables 4–8). The effect of cloudiness on the magnitude of the MRT is clearly shown; on the overcast day the MRT is only slightly higher than the air temperature during daytime. It should be noted, however, that these results may be subject to several errors, which include the uncertainty of the ratio between the direct and diffuse components of the solar radiation, the likely underestimation due to the missing reflected component and the uncertainty in RayMan's estimation of surface temperatures (see the Materials and Methods section). Nevertheless, the magnitude of the MRT for the "clear" day agrees well with the measurements of Ali-

Table 5 Input data for the calculation of the physiological equivalent temperature (PET) for the street canyons described in Table 2 on 7th May (partly cloudy day): air temperature, relative humidity and global radiation.

	Air temperature (°C)					Relative humidity (%)					Global solar radiation[a] (W/m²)				
Hour	BoC	DMP	GRB	NUG	UoM	BoC	DMP	GRB	NUG	UoM	BoC	DMP	GRB	NUG	UoM
1	29.4	27.8	28.3	25.3	25.1	84.7	90.9	86.0	100.0	100.0	0	0	0	0	0
2	28.9	28.0	27.8	25.8	25.0	85.4	89.7	87.8	100.0	99.2	0	0	0	0	0
3	28.2	27.6	27.2	25.5	24.9	85.0	87.5	87.5	99.4	99.0	0	0	0	0	0
4	28.6	27.9	27.8	26.3	26.1	87.4	89.1	87.4	97.8	99.4	0	0	0	0	0
5	29.4	28.3	28.4	26.3	26.5	81.8	85.4	86.0	99.6	100.0	0	0	0	0	0
6	29.5	28.6	28.9	27.7	26.9	79.4	83.7	81.8	93.1	93.9	0	0	0	0	0
7	29.5	28.3	28.5	27.8	27.1	80.5	83.8	83.2	92.4	94.4	3	3	4	4	1
8	30.1	28.9	28.8	28.1	27.7	74.0	79.0	78.3	89.4	90.4	47	40	54	58	46
9	31.1	29.6	29.7	29.1	28.4	71.9	77.6	75.1	83.5	87.2	108	92	124	134	105
10	31.4	30.5	30.5	30.2	29.3	72.7	77.5	74.9	84.2	84.2	174	147	199	216	170
11	31.0	31.4	31.2	31.6	30.1	75.1	75.6	73.2	78.4	80.8	258	218	296	320	252
12	31.7	31.6	31.7	32.5	30.6	72.6	74.5	71.5	74.2	79.0	310	262	355	384	302
13	32.0	32.3	32.0	33.8	31.3	70.2	69.1	69.1	69.1	74.3	355	300	406	439	346
14	32.3	32.9	32.2	34.7	31.8	69.6	68.0	68.4	66.5	74.6	326	276	373	403	318
15	32.5	32.6	32.6	35.0	32.0	69.4	68.3	67.1	65.2	72.9	355	99	406	440	346
16	31.5	31.9	31.8	33.3	31.3	73.2	72.0	71.4	70.9	74.8	141	39	161	175	137
17	28.9	28.9	29.5	30.2	30.7	84.2	84.4	82.9	87.1	77.5	73	20	83	90	71
18	29.7	29.1	28.9	29.6	30.2	80.1	85.4	84.7	88.3	80.2	78	22	45	96	76
19	29.7	29.0	29.0	29.7	29.4	80.6	87.0	84.4	88.6	85.5	4	3	5	6	4
20	29.0	28.1	28.9	29.0	28.6	86.6	89.2	85.7	91.1	89.9	0	0	0	0	0
21	29.0	28.1	29.1	28.5	28.1	84.4	90.3	83.2	92.7	93.4	0	0	0	0	0
22	29.7	28.0	29.2	28.2	28.1	80.0	88.6	79.9	94.1	93.3	0	0	0	0	0
23	29.7	28.1	29.3	28.0	27.9	80.5	88.3	79.5	95.0	93.7	0	0	0	0	0
24	29.6	28.2	29.3	28.0	27.5	80.6	86.1	79.8	95.5	95.3	0	0	0	0	0

a Calculated at 1 m height for an object on the sunny side of the street according to Eq. 3.

Toudert et al. (2005) on a clear summer day in a hot, dry city in Algeria.

The calculated values of the physiologically equivalent temperature (PET) are shown in Figs. 10–13. On the 3rd of May (clear day), the wind speed was measured on only one occasion at each site (and not simultaneously), but the measured value has, nevertheless, been assumed to be valid for the whole day. On the 7th of May (a partly cloudy day), only a few measurements of the wind speed were taken, but the relative difference between the sites was assumed to be the same as on 3rd May. On the 6th of May (an overcast day) no wind measurements were taken and therefore the wind speeds of 3rd May were used.

Fig. 10 shows the PET calculated under clear sky conditions, where the daytime values are related to someone exposed to solar radiation (i.e. choosing to walk on the sunny side of the street). During the day, the PET values of all the sites are generally above the upper comfort zone limit of 33°C suggested above, and during the period 11:00 – 16:00 h they by far exceed this limit and the thermal comfort is obviously very poor. The main reason for the extremely high daytime PET values, in this case, is the exposure to direct solar radiation. The Bank of Ceylon (BoC) site in the central business district, which is open to the sea breeze, has the least discomfort. Note the difference with the Galle Road site in Bambalapitiya (GRB),

Table 6 Input data for the calculation of the physiological equivalent temperature (PET) for the street canyons described in Table 2 on 6th May (overcast day): air temperature, relative humidity and global radiation.

	Air temperature (°C)					*Relative humidity (%)*					*Global solar radiation[a] (W/m²)*				
Hour	*BoC*	*DMP*	*GRB*	*NUG*	*UoM*	*BoC*	*DMP*	*GRB*	*NUG*	*UoM*	*BoC*	*DMP*	*GRB*	*NUG*	*UoM*
1	29.9	29.7	29.8	29.5	29.2	79.1	78.9	75.0	81.3	82.9	0	0	0	0	0
2	29.9	29.7	29.8	29.4	29.5	78.8	78.1	74.3	81.6	82.4	0	0	0	0	0
3	29.8	29.6	29.8	29.3	29.3	79.4	78.7	74.7	81.5	83.5	0	0	0	0	0
4	29.7	29.7	29.4	29.2	28.9	80.0	79.0	77.1	84.4	86.9	0	0	0	0	0
5	29.6	29.3	29.2	28.0	28.9	82.2	80.7	78.9	91.6	86.1	0	0	0	0	0
6	29.8	29.5	29.4	28.5	29.1	80.5	79.4	77.6	87.8	84.3	0	0	0	0	0
7	29.6	29.7	29.5	28.8	29.1	81.4	80.3	78.8	88.3	85.5	1	1	1	2	1
8	29.6	29.9	29.7	28.8	29.0	79.6	78.5	76.8	89.7	87.1	26	17	35	41	25
9	30.0	30.4	30.4	29.5	29.3	77.4	76.1	73.5	86.2	84.1	56	36	75	87	53
10	30.1	30.5	30.5	29.5	29.6	78.0	75.8	73.7	84.3	82.6	32	21	43	50	30
11	28.8	29.2	29.6	28.5	29.6	82.8	82.0	77.4	90.9	81.1	21	13	28	32	20
12	28.2	27.8	27.9	26.6	27.3	83.3	86.0	79.1	92.5	93.0	21	14	28	33	20
13	25.2	25.0	25.6	25.3	25.3	89.7	89.4	90.0	99.4	100.0	15	10	20	23	14
14	23.9	23.8	24.4	24.2	24.6	94.0	92.4	89.9	98.4	100.0	20	13	27	31	19
15	24.5	24.3	24.3	24.1	24.2	87.9	88.0	87.8	94.9	100.0	29	19	39	46	28
16	26.0	24.9	24.9	24.4	22.9	76.5	82.2	80.9	89.3	91.0	29	19	39	45	28
17	26.6	25.9	25.8	25.3	23.8	79.0	84.0	79.1	90.1	95.5	36	23	48	55	34
18	25.6	25.3	25.2	25.5	24.3	84.8	86.9	83.2	92.6	94.3	43	27	57	66	40
19	25.4	25.3	25.2	25.5	24.3	87.5	88.7	84.8	93.0	95.0	9	5	11	13	8
20	27.1	25.6	26.2	25.0	24.0	85.0	89.5	86.4	97.3	100.0	0	0	0	0	0
21	28.0	26.5	27.1	25.1	24.2	84.0	90.6	84.8	99.3	100.0	0	0	0	0	0
22	28.7	27.2	28.4	25.0	24.7	84.5	89.9	83.4	99.5	100.0	0	0	0	0	0
23	29.4	27.0	28.9	25.1	24.5	82.2	89.9	81.6	99.6	100.0	0	0	0	0	0
24	29.6	26.9	27.4	25.2	24.8	82.8	90.0	84.6	100.0	100.0	0	0	0	0	0

a Calculated at 1 m height for an object on the sunny side of the street according to Eq. 3.

which is also very close to the sea, but where the sea breeze is blocked by a row of buildings. The most uncomfortable sites are Pagoda Road in Nugegoda (NUG) and Prince Street in Pettah (DMP). The difficult conditions at the NUG site could be explained by its location far from the coast, which means it is least affected by the sea breeze (the air temperature is thus higher). The DMP site has the most compact urban form, which reduces wind speed and, thus, results in high PET values. Note, however, the sharp drop in PET at the DMP site at 15:00 h; at this time buildings start to provide shade over the entire street.

Fig. 11 shows the PET values for the same day as Fig. 10 for someone choosing the shady part of the street (when shade exists). At the sites BoC, DMP, GRB and, especially, at the University of Moratuwa site (UoM), this improves the thermal comfort conditions considerably, due to the presence of medium or high-rise buildings and some vegetation (except at the DMP site). The UoM site has horizontal shading devices along its northern façade, which makes it possible to have shade there throughout the day. Note, however, that around noon, none of the sites, except that of UoM, provides sufficient shade because of the high solar elevation. At the NUG site, where there is negligible shade, conditions are very poor throughout the day – shade is only available there in the early morning and in the late afternoon.

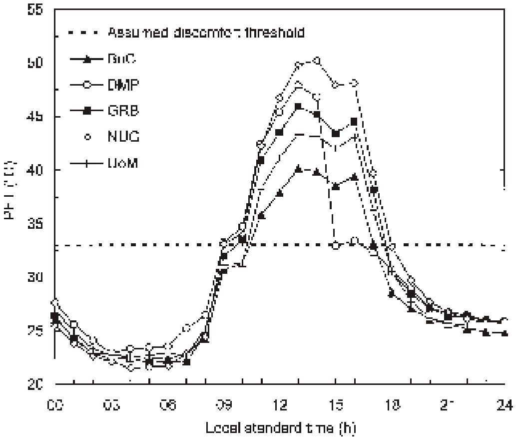

Fig. 10 *Calculated PET values on a clear day (3rd May 2003) for a subject exposed to solar radiation (being on the sunny side of the street). The assumed upper discomfort limit is included as a reference.*

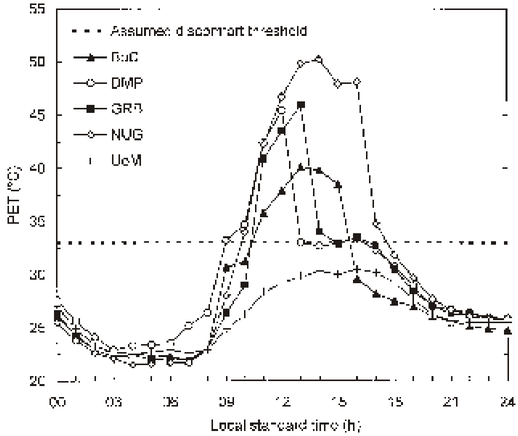

Fig. 11 *Calculated PET values on a clear day (3rd May 2003) for a subject positioned on the shady side of the street (where possible). The assumed upper discomfort limit is included as a reference.*

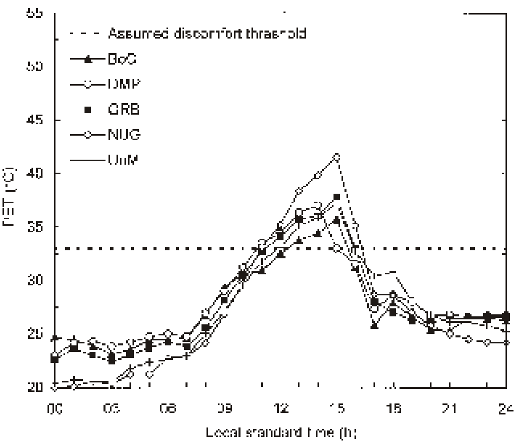

Fig. 12 *Calculated PET values on a partly cloudy day (7th May 2003) for a subject positioned on the sunny side of the street. The assumed upper discomfort limit is included as a reference.*

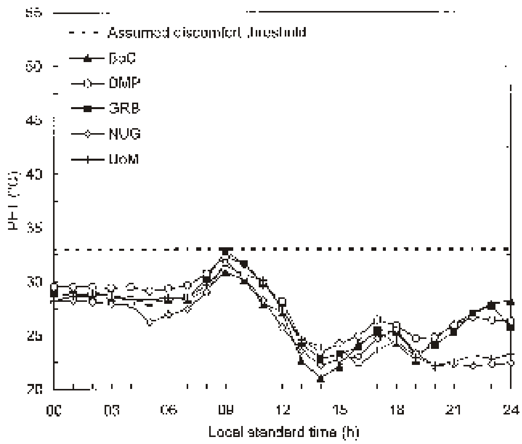

Fig. 13 *Calculated PET values on an overcast day (6th May 2003). The drop starting at around noon is due to rainfall. The assumed upper discomfort limit is included as a reference.*

Table 7 *Wind input data for the calculation of PET for the street canyons described in Table 2 on 3rd, 6th and 7th May 2003.*

Wind speed (m/s)					
Day	*BoC*	*DMP*	*GRB*	*NUG*	*UoM*
3 May	2.5	0.6	1.7	2.2	1.0
6 May	2.5	0.6	1.7	2.2	1.0
7 May	3.9	1.0	2.6	3.4	1.5

Fig. 12 shows the calculated PET values on a partly cloudy day for someone exposed to the sun. Under this sky condition the differences between the sites are smaller than under clear sky conditions

(Fig. 8), but although the solar radiation is considerably less, the PET values are above the assumed discomfort threshold (PET = 33°C) between 11:00 and 16:00 h. Shading will also, therefore, have a positive effect during partly cloudy days.

Fig. 13 shows the calculated PET values on an overcast day. The PET varied less between the sites – both by day and by night – and the assumed thermal comfort threshold was never exceeded although daytime temperatures and humidity were high. The most comfortable areas were those with the greatest wind speeds. The afternoon drop is due to rainfall.

Figs. 10–13 show that during the period between sunset and early morning, the PET values are fairly low, and sometimes even below the lower comfort limit suggested above. The variation between the sites is much less than during the day, but the dispersed NUG site tends to have the lowest PET values and the compact DMP site the highest. This is because the wind speed is relatively high at NUG and low at DMP, as well as the fact that the sky view factor is big (thus, cooling through net long-wave radiation loss to the sky is efficient) at NUG and low at DMP.

Table 8 Cloud cover data for the calculation of MRT and PET for the street canyons described in Table 2 for a clear (3rd May), a partly cloudy (7th May) and an overcast day (6th May).

Cloud cover (octas)				*Cloud cover (octas)*			
Hour	3 May	6 May	7 May	Hour	3 May	6 May	7 May
1	6	3	5	13	4	8	6
2	4	3	5	14	4	8	6
3	2	4	5	15	4	8	6
4	3	5	5	16	5	7	7
5	4	5	5	17	6	7	7
6	5	6	5	18	7	6	8
7	4	6	5	19	6	6	8
8	4	7	6	20	4	5	8
9	3	7	6	21	3	5	8
10	3	7	6	22	3	5	8
11	4	8	6	23	3	5	8
12	4	8	6	24	3	5	8

The effect of H/W ratio

The calculated thermal comfort conditions, expressed in PET, show the importance of shading for the improvement of daytime comfort. Given the importance of MRT to outdoor thermal comfort, this is to be expected. For example, the MRT for the site DMP drops about 30 K on a clear day (Fig. 7) when the buildings provide shade to the street in the afternoon. A similar difference in MRT between solar exposure and shade was also found by Ali-Toudert et al. (2005) in a city in southern Algeria. The results in fact indicate that a compact urban form (high H/W ratios) can provide more comfortable conditions than a dispersed urban form. Ahmed (2003) came to a similar conclusion about the summer climate of Dhaka, Bangladesh, where he found that semi-enclosed spaces, which restrict air movement, but provide shade, were sometimes comfortable during the hottest period of the day. This is contradictory to the common belief that in the hot, humid tropics, the most important design strategy is to provide air movement. During the hours around noon, approximately 10:00–14:00 h, even high-rise buildings can, however, only provide limited shade. To also achieve shade during this time of the day some type of overhead shading is required, e.g. wide tree canopies, pedestrian arcades or other types of shading device.

Tower buildings are well adapted to the hot, humid climate as they do not obstruct the air flow as long as their density is low. A mixture of high-rise towers and lower buildings creates an uneven fabric and such an arrangement can, therefore, increase air movement (de Schiller and Evans 1998; Aynsley and Gulson 1999). High rise buildings may be restricted to high socio-economic status residential and office building precincts.

Street canyons with high H/W ratios will, however, have a negative effect at night since shading reduces the heat loss through net long-wave radiation to the sky. The results indicate, however, that the positive effect of shading during daytime is bigger than the negative effect at night. However, radiation loss to the sky also helps to cool down the buildings and high H/W ratios may, therefore, be unfavourable for indoor night comfort, which is essential for sleeping. The appropriate H/W ratio will, therefore, depend on the type of neighbourhood; higher nocturnal temperatures may be more acceptable in commercial areas than in residential areas.

The effect of street orientation

For streets oriented in a north–south direction (such as the GRB and the NUG sites) shade can be provided by the buildings in both the morning and the afternoon if the H/W ratio is high enough. However, around noon shade cannot be provided by the buildings alone. For those streets oriented in an east–west direction (like the BoC, DMP and UoM sites), there will be shade on the southern side of the street during the period October–March provided buildings on this side of the road are sufficiently tall. During the rest of the year the sun is in the zenith position, or slightly to the north, making it difficult to achieve shade without a tree canopy, arcades or other types of shading devices.

The shading strategies suggested for north-south oriented streets are practical in Colombo, given the fact that the city is elongated along its north-south direction. Thus many of the city's streets could benefit from the above proposal. At the same time, the fact that the Indian Ocean is to the west of the city adds practicality to the other proposal concerning east-west streets. Broad east-west oriented streets have the additional advantage of facilitating deeper penetration of sea breeze inland.

The effect of ground cover and proximity to the sea

Although the ground cover around each site varied considerably (see Table 1), this did not have a significant impact on thermal comfort. The reason could be that, at street level, the surface materials were similar on all sites; typically heavy materials such as asphalt, concrete, brick and plaster, which have a high thermal capacity. The direct solar radiation hit mainly horizontal surfaces, which were fairly dark in colour and thus absorbed most of the incoming radiation. The large temperature differences found between sunlit and shaded paving (up to 20 K) show the importance of keeping surfaces cool to minimize the sensible heat loss. Lower surface temperatures can also be achieved by using lighter, less heat absorbent colours.

The proximity and openness to the sea is also important as it enhances the possibility to benefit from the cooling effect of the sea breeze. Except during the latter part of the summer monsoon (especially June-August), Colombo's typical wind speeds are in the range of 0.7–1.1 m/s (data for the last 35 years from Colombo Meteorological Station which is situated about 3 km inland). Compared to the weak monsoon winds, our measurements at or near the shore-line indicated wind speeds in the range of 1.5–5.5 m/s. The sea breeze effect is clearly illustrated by the difference between the Bank of Ceylon site in the central business district (BoC) and the Galle Road site in Bambalapitiya (GRB). Although both are close to the sea, the former, which is open to the sea, is more comfortable due to the lower air temperature of the sea breeze and the higher wind speeds, whereas the latter has a row of buildings along its western side effectively blocking the sea breeze. The findings of this research agree with the study of Saaroni et al. (2000), who found that the cooling effect of the sea breeze in Tel-Aviv was considerable in the afternoon, especially in those places open to the sea.

Conclusions

The results of this study have implications on design guidelines for climate-conscious urban planning and design. Possible strategies to improve outdoor thermal comfort in the city of Colombo include:

- Allowing a more compact urban form with deeper street canyons to provide shade at pedestrian level. Care has to be taken, however, especially in residential areas, because the possibility of natural ventilation and night-time cooling of buildings decreases with an increased H/W ratio. Deep canyons are also a disadvantage in polluted areas since dispersion is less effective in shallow canyons.
- Providing shade within the street canyons during the hours around noon by utilising large tree canopies, covered walkways, pedestrian arcades, awnings or other types of shading.
- Encouraging airflow, which is moderate in the case of Colombo, by using irregular positioning of buildings and creating variations

in building height. Tower buildings, if positioned a sufficient distance apart, also stimulate air movement.

- Opening up the coastal strip of the city by widening the roads, which run perpendicular to the coast so that they can act as channels. This will permit the sea breeze to penetrate further into the city and is especially important because of the weak macro-level winds in equatorial cities such as Colombo.

Future studies should include simulations to examine the effect of different urban design on outdoor thermal comfort. There is also a need to explore people's subjective perception of the thermal environment – through the use of questionnaires and interviews – and relate it to calculated comfort indices in order to determine acceptable comfort limits. This is particularly important in the face of growing acceptance of the "acclimatization effect" (e.g. the idea of "adaptive thermal comfort" pioneered by Humphreys (1996), Nicol and Humphreys (2002) and others. See also de Dear and Brager, 2001; the most recent revision to thermal comfort standards issued by the American Society of Heating Refrigerating and Air Conditioning Engineers – ASHRAE Standard 55-2004 [ASHRAE, 2004]). Parallel to such a survey, it is also necessary to carry out continuous meteorological measurements, including both wind speed and mean radiant temperature, within street canyons and in close proximity to street users. Further field studies are needed to evaluate the effect of different types of overhead shading devices on outdoor thermal comfort.

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Paper IV

Manuscript.

Simulations of urban microclimate and outdoor thermal comfort in the hot dry city of Fez and in the hot humid city of Colombo

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Abstract

The outdoor environment is deteriorating in many tropical cities, which leads to a number of problems related to the well-being of humans. It is therefore important to improve the microclimatic conditions around buildings in urban environments. The aim of this study was to evaluate the effect of street design on outdoor thermal comfort in the hot dry climate of Fez, Morocco and in the hot humid climate of Colombo, Sri Lanka and to suggest possible improvements. The analysis was carried out through numerical modelling using ENVI-met, a three-dimensional model that predicts the microclimate in urban environments. Simulations were run for several street designs and included the effect of architectural details such as colonnades, shading trees and reflectivity of façades and street. The thermal comfort was estimated by calculating the physiologically equivalent temperature (PET). The simulations showed that canyons with high H/W ratios, where buildings provide shade, represent an advantage for both the summer climate of Fez and for Colombo. However, for the winter season in Fez, streets with low H/W ratios are preferable. East-west streets are the most problematic as concerns thermal comfort. For both Fez and Colombo they need H/W ratios about 4 to provide shade. For north-south streets an H/W ratio of about 2 provides acceptable conditions for Colombo and for both seasons in Fez. To provide thermal comfort in winter in Fez some streets oriented east-west should have a H/W = 0.67 with a colonnade on its northern side to provide solar access. In Colombo, spacing between buildings is preferable to permit air flow. This is especially important near the coast where some east-west streets could have as low H/W ratios as 0.5. For both cities it is recommended that buildings have no front setbacks, in order to increase the possibilities of shade for pedestrians. Moreover, overhead shading should be provided in the

form of projected upper floors, colonnades, shading trees or other devices to improve thermal comfort for pedestrians.

1 Introduction

The outdoor environment is deteriorating in many tropical cities due to rapid urbanization. This leads to a number of problems related to the health and well-being of humans and negatively affects social and commercial outdoor activities. A poor outdoor climate will also negatively affect the indoor climate and lead to increased energy use. It is therefore important to improve the microclimatic conditions around buildings in urban environments.

Field measurements in hot dry climates (Ali-Toudert et al. 2005, Johansson 2006) and in hot humid climates (Ahmed 2003, Emmanuel & Johansson, 2006) indicate that urban design has a significant impact on the urban microclimate. Although the link between urban geometry and nocturnal air temperatures (the nocturnal urban heat island) is well known, intra-urban temperature differences may be bigger by day (Emmanuel and Johansson 2006, Johansson 2006). Climatic parameters such as air temperature and wind speed have been shown to depend on the height to width (H/W) ratio of urban canyons. Moreover, both measurements and simulations have shown that solar radiation and long-wave radiation from warm surfaces reach very high levels in hot climates, which leads to high mean radiant temperatures (MRT) can reach very high values (Ali-Toudert et al. 2005, Johansson and Emmanuel 2006).

Studies on outdoor thermal comfort conditions in hot dry climates (Ali-Toudert et al. 2005, Ali-Toudert and Mayer 2005 and 2006, Johansson 2006) and hot humid climates (Ahmed 2003, Johansson and Emmanuel 2006) have indicated that uncomfortable conditions are common. In hot humid climates and during the summer season in hot dry climates, the outdoor thermal comfort conditions are far above acceptable comfort standards, especially around midday. The worst conditions were found in wide streets with low-rise buildings and no shading trees. During the winter in hot dry Fez (Johansson 2006), thermal comfort was found to be below normal discomfort levels, especially in deep canyons.

In order to create thermally comfortable urban environments it is important to be able to predict the effect of urban design on urban microclimate and outdoor thermal comfort. This would preferably be done through simulations as it would require extensive measurements to cover a wide range of urban forms and as it would not be possible to measure non-existing designs.

However, there are few simulation studies on outdoor thermal comfort, especially in tropical climates. One reason is probably the complexity of the urban climate which makes such modelling difficult. Moreover, many models deal with the local or meso scales, and do not give detailed results at street level. Many of the existing urban canopy layer models, such as the models of Mills (1997) and Kusaka and Kimura (2004), do not exist as developed softwares and give few output variables. Other models such as the CTTC model (Swaid and Hoffman 1990) are empirical in character and may thus be restricted to one particular climate.

ENVI-met (Bruse 2006) is one of few user friendly, easy to use softwares which provide a detailed output on the micro-scale. The programme was used recently in studies in tropical climates. Ali Toudert and Mayer (2006) used it to simulate outdoor thermal comfort in a hot dry desert city in Algeria. In another study in the same city, Ali Toudert and Mayer (2005) studied the influence of vegetation. However, in these studies only the warm season was studied. Yu and Hien (2006) used ENVI-met to study the cooling effect of urban parks in the hot humid climate of Singapore. The latter study was, however, limited to parks.

In this paper, the relationship between street design and outdoor thermal comfort in the hot dry city of Fez, Morocco and the hot humid city of Colombo, Sri Lanka was studied using ENVI-met. This software, which has proven to give realistic results in previous studies (Ali-Toudert and Mayer 2006, Jansson 2006), calculates all environmental parameters needed to calculate thermal comfort indices. The outdoor thermal comfort was estimated by calculating the Physiologically Equivalent Temperature (PET).

2 Methodology

Study areas

Fez (34.0°N, 5.0°W) has hot dry summers and fairly cold winters and diurnal temperature fluctuations are large (Johansson 2006). In July, mean diurnal temperature vary between 16 and 34°C and the vapour pressure varies between about 12 and 15 hPa. In January, mean diurnal temperatures vary between 4 and 15°C and the vapour pressure varies between about 9 and 12 hPa. Solar radiation is intense in summer with a large part of direct radiation. In winter, the solar radiation is less and the diffuse component is higher than in summer.

Colombo (6.9°N, 79.9°W) has a hot humid climate with small annual and diurnal variations (Emmanuel and Johansson 2006). In May, the most warm and humid month, temperatures vary between 26 and 32°C and the vapour pressure between about 30 and 35 hPa. Solar radiation is intense all year round with a large part of diffuse radiation. The climate in Colombo is moderated by the cooling effect of the westerly afternoon sea breeze (Emmanuel and Johansson 2006).

Simulation model

The microclimate at street level was simulated with ENVI-met 3.0 (Bruse 2006). The programme, which is available for free, uses a three-dimensional computational fluid dynamics (CFD) and energy balance model. The model takes into account the physical processes between the atmosphere, ground, buildings and vegetation and simulates the climate within a defined urban area with a high spatial and temporal resolution enabling a detailed study of how the microclimate varies within the studied space over time. The input data to the model consists of the physical properties of the urban area of study (buildings, soil and vegetation) and limited geographical and meteorological data. The wind (speed and direction) is constant throughout the simulations. The simulation period is normally one complete diurnal cycle. The model gives a large amount of output data including the necessary variables to be able to calculate thermal comfort indices: wind speed, air temperature, humidity and mean radiant temperature.

Model structure

The main model in the programme is three-dimensional (3D) and extends from the ground to about double height of the highest object. The lateral borders of the main model are surrounded by a nesting area – a buffer zone without buildings and vegetation. Between the top of the 3D model and the upper boundary of the model, at 2500 m, a 1D model is used. Below the main 3D model there is a 1D soil model extending to a depth of 2 m.

The main 3D atmospheric model uses fundamental laws of fluid dynamics and thermodynamics and solves the energy balance at urban surfaces. It simulates the speed and direction of the air flow, atmospheric turbulence, air temperature, humidity, short- and long-wave radiation fluxes, dynamic heat storage and heat transfer in the ground and building surface temperatures. The area consists of 3D grid cells which contain soils, buildings, vegetation or open spaces. The typical grid resolution is 0.5–10 m.

Buildings are modelled as blocks where width and length are multiples of grid cells. Since the bottom of a building does not need to be in contact with the ground it is possible to simulate projecting upper floors and colonnades. The heat transport to or from the buildings is determined from the temperature difference between the surface and the constant indoor temperature.

The vegetation sub-model simulates the fluxes of heat and vapour between the atmosphere and the vegetation including the evapotranspiration. The vegetation is treated as vertical columns with the width equal to the grid cell width whereas the height depends on the type of vegetation.

The soil sub-model calculates the temperature and soil moisture for soil profiles that are divided into different layers and whose thickness increases with depth. Each soil layer has different hydraulic and thermal properties. The latter include thermal conductivity, heat capacity and density. The heat storage is thus accounted for. The surface can be porous or sealed with impervious materials such as asphalt or concrete. The soil surface can have varying surface roughness and reflectivity (albedo). There is one soil profile for each horizontal grid point.

Calculations

To be able to perform the simulations, ENVI-met needs the geographical position (latitude and longitude) and cloud cover to determine the components of direct and diffuse solar radiation. The calculations start with an initialisation phase which requires the wind speed and direction at 10 m height, initial temperature (which is also the constant temperature at the upper model border at 2500 m), specific humidity at 2500 m and initial relative humidity at 2 m. Moreover it needs the initial temperatures and the soil moisture in the soil layers of 0–0.2 m, 0.2–0.5 m and 0.5–2 m. During the initialisation phase, the vertical profiles of wind, temperature and humidity are determined in the air layer of 0–2500 m. Similarly, the vertical profiles of temperature and moisture in the soil is determined during this phase.

All calculation in ENVI-met uses the potential temperature, that is, correction is made for the effect of decreasing air temperature with height (see e.g. Oke 1987)

Calculation of the mean radiant temperature

The mean radiant temperature (MRT) is a key variable in determining the thermal comfort outdoors. At the height z, it is claculated by ENVI-met as (Ali-Toudert and Mayer 2006):

$$MRT = \left[\frac{1}{\sigma}\left(E(z) + \frac{\alpha_k}{\varepsilon_p}\big(D(z) + f_p I(z)\big)\right)\right] \qquad (1)$$

where σ is the Stefan-Boltzmann constant (= 5.67×10-8 W/m^{2}K^4), *E(z)* is the long-wave radiation from the sky, façades and ground, α_k (= 0.7) and ε_p (= 0.97) are the body's absorption of short and long-wave radiation respectively *D(z)* is the diffuse and diffusely reflected solar radiation, f_p is the body's surface projection factor, and *I(z)* is the direct solar beam.

At pedestrian level, the incoming long-wave radiation E(z) is approximated as:

$$E(z) = 0.5[(1–SVF(z)E_w + SVF(z)E_{sky}] + 0.5 \times E_g \qquad (2)$$

where SVF is the sky view factor and E_w, E_{sky} and E_g are the incoming long-wave radiation from the façades, sky and ground respectively.

Limitations with the present version

The version of ENVI-met used in this study, version 3.0, has some shortcomings. Buildings have no thermal mass and this may affect surface temperatures of the façades and, consequently, the mean radiant temperature as well as the air temperature at street level. Moreover, individual properties of buildings cannot be set; all buildings have the same indoor temperature (constant value), reflectivities of walls and roofs and U-values of walls and roof. The building geometry is limited and there are no possibilities to put shading devices on façades. Furthermore, as the climate is generated by the programme it does not consider the influence of large-scale meteorological phenomena. Finally, there are still few studies of validations against measurements although the model has been frequently used recently.

Calibration

One measurement site from each city from earlier studies (Johansson 2006, Emmanuel and Johansson 2006) was modelled in ENVI-met and the simulations were compared with measured results. The sites were modelled as accurately as possible as regards building geometry, street orientation, thermal properties of buildings as well as ground properties and measured meteorological data was used as input. As a result of the deviation between measured and simulated results modifications were made to some of the input data. The general input data used in the simulations are shown in Table 1.

Table 1 General conditions for the simulations.

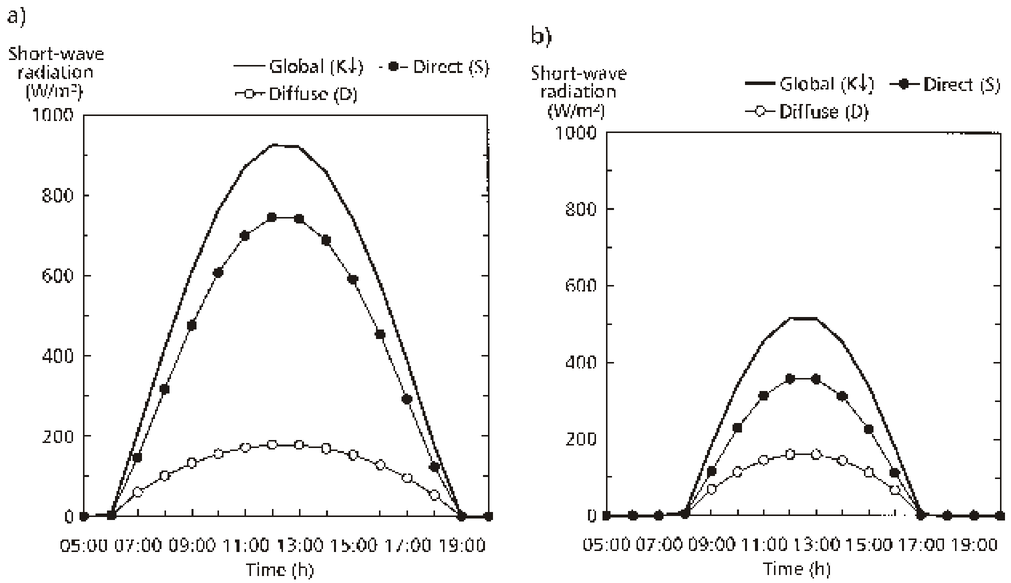
	Fez		*Colombo*
Latitude	*33.97°N*		*06.9°N*
Longitude	*04.98°W*		*79.9°E*
Date of simulation	*Summer 15 July '00*	*Winter 15 Jan. '00*	*3 May '03*
Clouds, high level (octas)	0	0	0
Clouds, medium level (octas)	0	2	0
Clouds, low level (octas)	1	0	4
Short-wave adjustment	0.85	1.00	1.12
Wind speed at 10 m height (m/s)	0.6	0.6	2
Initial temperature at 2500 m (°C)	15	9	28
Initial humidity at 2500 m (g/kg)	9	7	20
Relative humidity at 2 m height (%)	75	85	85

The calculated solar radiation had to be adjusted as it was either over or underestimated by ENVI-met (see Table 1). The corrected solar radiation used during the simulations are shown in Fig. 1. For the case of Fez, the solar radiation was adjusted to represent typical radiation for the summer and winter periods. For Colombo the solar radiation of a "clear" day was used according to Emmanuel and Johansson (2006).

It turned out that ENVI-met underestimated the diurnal temperature fluctuations. This has been observed in other studies also (Ali-Toudert and Mayer 2006, Jansson 2006). The reason given in the programme documentation (Bruse 2006) is that ENVI-met calculates the urban climate at a micro- or local scale and that larger regional (meso-scale) effects are not taken into account. However, in the case of Fez, more realistic temperature variations could be obtained by setting a low wind speed (0.6 m/s) as this makes ENVI-met use a different turbulence model. Nevertheless, there were still very small nocturnal air temperature differences in spite of the huge difference in height-to-width (H/W) ratio between the sites. It appears that ENVI-met failed to simulate the nocturnal heat island effect due to reduced SVF.

In the case of Colombo, it was not possible to put a low wind speed because the simulations became unstable and were interrupted. Instead the wind speed was put to 2 m/s, which is about the maximum wind speed measured at the Colombo met. station. Consequently, urban geometry had negligible impact on the air temperature in the Colombo case.

As a consequence of the low wind input value for the Fez case, the simulated wind speeds at street level were much lower than the measured values. However, also in the Colombo case, the simulated



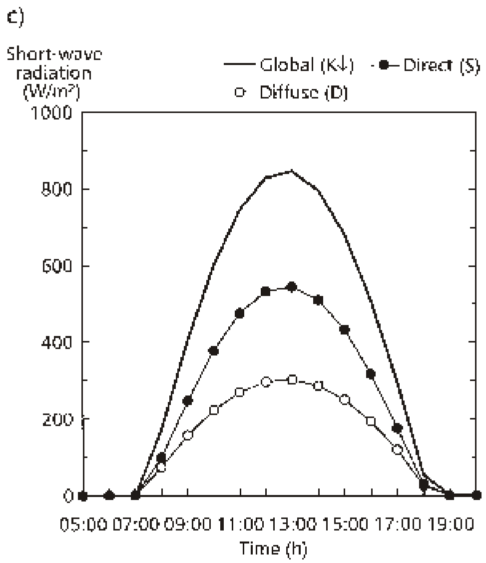


Fig. 1
Solar radiation on a horizontal surface calculated by ENVI-met for (a) the summer period in Fez (15 July), (b) the winter period in Fez (15 January) and (c) a clear day in May in Colombo (3 May).

wind speeds at pedestrian level were much lower than those that had been measured, below 0.1 m/s.

As the simulated wind speeds for both the Fez and Colombo cases were underestimated, the wind speeds used to calculate PET were based on measured values (Emmanuel and Johansson 2006, Johansson 2006), see Table 2.

To compensate for the fact that the buildings have no mass in ENVI-met, the thermal admittance ì for the street was increased. This property, which determines the ability of a surface to take up heat, is calculated as:

$$\mu = \sqrt{\lambda \; C} \tag{3}$$

where λ is the thermal conductivity (W/m°C) and *C* is the volumetric heat capacity (J/m^3 °C). It was assumed that the "active" canyon surface influencing the canyon air at pedestrian level consisted of the ground and the lowest 6 m of the façades, see Fig. 2. The increased thermal admittance of the street μ_{st*} was calculated as:

$$\mu_{st*} = \frac{12m \ \ \mu_{fac} + W \ \ \mu_{st}}{W} \qquad (4)$$

where $\mu_{faç}$ = the thermal admittance of the façades, W = street width (m) and μ_{st} = thermal admittance of the street. The thermal admittances of the street and façades were assumed to be 1700 J/m^{2}s$^{0.5}$°C (asphalt) and 1200 J/m^{2}s$^{0.5}$°C (plaster) respectively. The values of increased thermal admittance for the street μ_{st*} for the different H/W ratios are shown in Table 2.

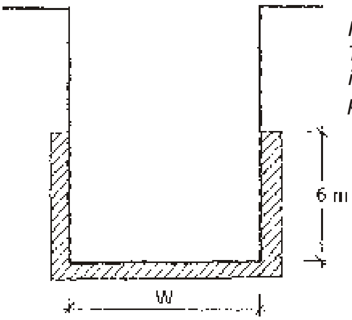


Fig. 2
The assumed "active" canyon surface influencing the canyon air at pedestrian level.

Table 2 Thermal admittance (μ_{st*}) of the street, vapour pressure (VP) and wind speed for the different H/W ratios in the simulations. μ_{st*} includes the thermal admittance of the façades according to eq. 4).

H/W ratio		*Fez, summer*		*Fez, winter*		*Colombo*	
	μ_{st*} (J/m^{2}s$^{0.5}$°C)	*VP (hPa)*	*wind speed (m/s)*	*VP (hPa)*	*wind speed (m/s)*	*VP (hPa)*	*Wind speed (m/s)*
0.12	1800					33.5	2.2
0.5	2300	13.5	0.8	10	0.8		
0.6	2500					33.5	1.0
1	2900	14	0.7	10.5	0.7		
1.3	3500					33.5	0.6
2	4100	14	0.6	10.5	0.6	33.5	0.5
4	6500	14.5	0.5	11	0.5	33.5	0.3
8	11500	15	0.4	11.5	0.4		

Parametric modelling

Model area and typified street canyons

The testing environment in the simulation part of this study was a street canyon (Fig. 3). The height of the buildings was kept constant at 12 m whereas the width of the canyon varied. In order to avoid influences from the ends of the canyon, the canyon was long, with a

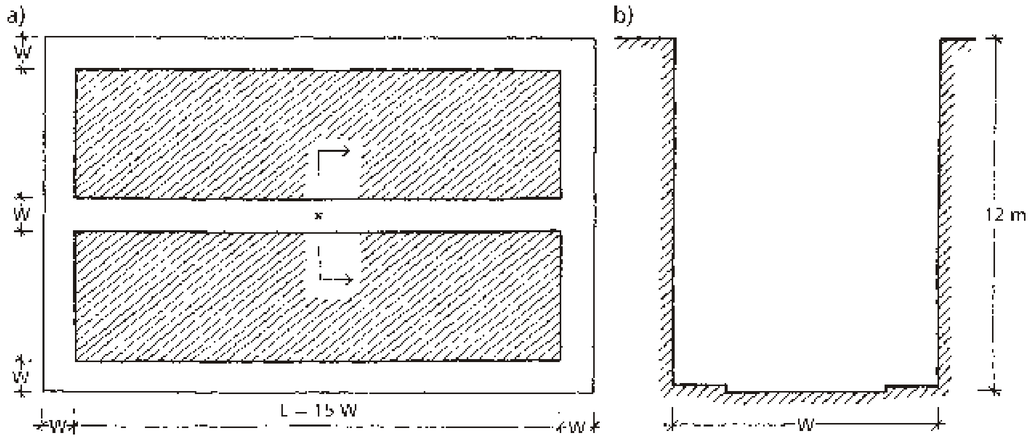


Fig. 3 (a) Model area and (b) the street canyon of the base case.

constant length-to-width ratio of 15, and the wind was always perpendicular to the long-axis of the canyon. The two buildings were enclosed by a wall of the same height as the buildings (12 m) in order to reduce the effect of advection from the surrounding "rural" area. The distance between the buildings and the wall was set equal to the width of the street (W). The reason for choosing a small model area was to limit the number of grids in order to restrict computation time. The area in Fig. 3a is to be seen as a part of a larger homogeneous area.

For each of the cities, a base case was created comprising a simplified urban canyon with typical geometric characteristics (H/W ratio), material properties, façade colours and ground elements. The input data of the base cases, which had no vegetation or shading devices, are shown in Table 3.

Table 3 Input data for the base cases in Fez and Colombo.

	Fez summer	*Fez winter*	*Colombo*
Building height, H (m)	12	12	12
Street width, W (m)	6	6	9
H/W ratio	2	2	1.3
Indoor temperature (°C)	26	20	26
U-value, walls ($W/m^2 °C$)	1.5	1.5	1.5
U-value, roof ($W/m^2 °C$)	1.5	1.5	1.5
Reflectivity, façades	0.3	0.3	0.4
Reflectivity, roofs	0.4	0.4	0.4
Reflectivity, street	0.3	0.3	0.3
Thermal admittancea μ, street ($J/m^2 s^{0.5} °C$)	4100	4100	3500

a Including the thermal admittance of the façades according to Fig. 2 and eq. 4.

Strategies for parametric modelling

The energy balance of a street canyon was used to identify strategies to improve the microclimate of the urban canyons modelled for each city. According to Oke (1987):

$$(K^* + L^*) + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A \qquad (5)$$

where K^* and L^* are net incoming short- and long-wave radiation respectively, Q_F is anthropogenic heat, Q_H is sensible heat, Q_E the latent heat from evapotranspiration, ΔQ_S represents the net heat storage in the canyon surfaces and ΔQ_A is the net advection through the sides of the volume. All fluxes are in W/m^2.

If advection and anthropogenic heat are neglected, which is reasonable if the area studied is assumed to be sufficiently large and if buildings are neither heated nor cooled, sensible heat can be expressed as:

$$Q_H = K^* + L^* - Q_E - \Delta Q_S \qquad (6)$$

In a warm climate, such as that of Colombo and of the summer in Fez, the strategy to improve the microclimate would be to minimize sensible heat Q_H. In the daytime, the strategies will thus include:

- Decreasing absorbed solar radiation $K^* = K\downarrow - K\uparrow$. This can be achieved through increased shade (to reduce the incoming solar radiation $K\downarrow$), either by increasing the H/W ratio or by using shading devices or shade trees. By using light colours, reflected radiation $K\uparrow$ can be increased. It should be noted that a decline in K^* through additional shade will automatically reduce cooling through long-wave radiation L^*. However, since K^* is dominant over L^* during the daytime, the main strategy is to lower K^*.
- Increasing latent heat Q_E. This can be achieved by using permeable surfaces and vegetation to increase evaporation and transpiration. The increase in Q_E is particularly efficient in hot dry climates where evaporation is strong. However, as rainfall is scarce, abundant irrigation is necessary.
- Increasing heat storage ΔQ_S. This can be achieved by using heavy materials with high thermal admittance in façades and ground elements. It should be noted that a high daytime ΔQ_S may be negative in a climate with warm nights, such as that of Colombo, since the heat stored in urban surfaces during the day will be released after sunset.

The strategies for a cold climate, such as the winter period in Fez, would be the reverse of those proposed above, that is, to maximize Q_H. Consequently, it is necessary to identify a compromise between summer and winter requirements.

Similarly, the heat balance of the human body (Höppe 1999) can be used to identify strategies to improve thermal comfort in different climates. In warm conditions, the heat loss through the evaporation of moisture diffused through the skin E_{dif}, as well as convective C_{res} and evaporative E_{res} heat loss through respiration are normally small compared to the other heat fluxes in the heat balance equation (see e.g. Höppe 1999). Consequently, the energy balance is maintained primarily through a balance between metabolic heat production M, convective and radiant heat losses $(C+R)$ and the loss of heat through the evaporation of sweat E_{sw}. However, the latter may also be restricted in hot humid conditions, such as in Colombo, due to the high levels of humidity. Moreover, in warm climates, the sensible heat loss *(C+R)* is small and *R* can often be negative (radiative heat gain). It is therefore very important to maximize radiative and convective heat losses. Under warm conditions, the strategies to improve comfort conditions include:

- Increasing radiant heat loss (or minimising heat gain) *R*. This is achieved by lowering MRT, mainly through the provision of shade. Shade is needed both to minimize exposure to solar radiation and to lower surface temperatures. Surface temperatures can also be lowered through the use of lighter colours.
- Increasing convective heat loss *C*. This is achieved by increasing air movements.

In a cold climate, such as during the winter in Fez, the strategy would be precisely the opposite.

Parametric study

The simulations were performed as a parametric study in which different characteristics of the urban canyons were subjected to variation. Only one parameter was changed at a time in order to determine the relative influence of each. The effect of the following design parameters on microclimate and thermal comfort were studied:

- H/W ratio
- Street orientation
- Reflectivities (colours) of ground and façades
- Thermal properties of ground materials
- Colonnades for shading of pedestrians
- Shading trees
- Spacing between buildings (only Colombo).

The design parameters studied are shown in Table 4. The H/W ratios were chosen to reflect the measurement sites and the ratios commonly found in each city. Street orientation for all simulations was east-west. However, the north-south orientation was also studied for each H/W ratio. Reflectivity values represent realistic ranges, varying from dark to light façades, as well as from dark to medium-dark

Table 4 The simulation cases for Fez and Colombo.

			Base case		
H/W ratio[a], Fez	0.5	1.0	2	4	8
Colombo	0.12	0.6	1.3	2	4
Reflectivity, façades	0.2	0.4	0.4[b]	0.6	0.8
ground	0.1	0.2	0.3	0.3	0.4
Thermal adm., street[c] ($J/m^2s^{0.5}$°C)	600	2500	4100	6500	
Colonnades			No	Yes	
Shading trees			No	Yes	
Spacing between buildings (Colombo)			No	Yes	

a Both east-west and north-south orientations were tested.
b The reflectivity of the façades was 0.3 in the base case for Fez.
c Including the thermal admittance of the façades according to Fig. 2 and eq. 4.

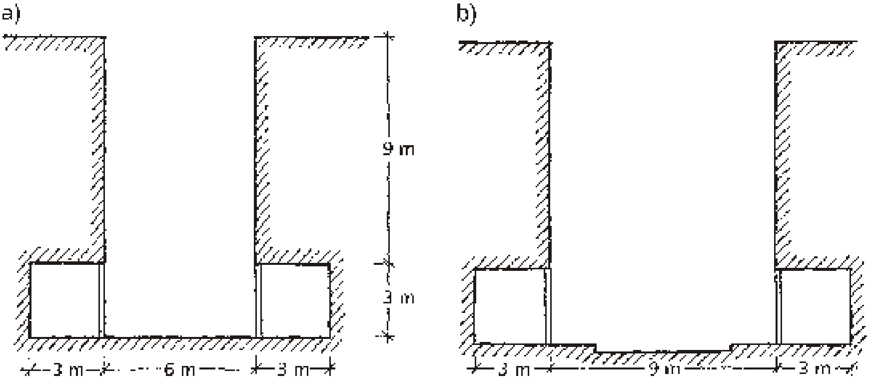


Fig. 4 The simulation cases for east-west oriented street with the colonnades on both sides. (a) Fez, (b) Colombo.

streets. As regards the effect of thermal mass, the lower thermal admittance value corresponds to light materials in the form of wooden façades and ground in the form of a light dry soil. The higher value corresponds to façades and ground of high density stone.

The effect of colonnades was simulated according to Fig. 4. In Fez, the colonnade was placed on the northern side of an east-west oriented street with a H/W ratio of 0.9, in order to admit solar radiation in winter. In Colombo, a street with colonnades on both sides of the street was used. The effect of shading trees was simulated by placing a continuous row of trees along one of the façades in the base case, see Fig. 5.

To simulate the effect of detached blocks on the wind speed, 9 m wide corridors perpendicular to the street were introduced in the model area of Fig. 3a.

As a final step, all of the changes found to improve the microclimate and thermal comfort at street level were combined to form a “best case” scenario. In the case of Fez, solutions were sought that could improve thermal conditions for both the summer and winter seasons.

Simulation of microclimate and calculation of thermal comfort

The simulations normally started at around sunrise and ran for at least 12 hours. The time step varied between two and ten seconds. The lower value was for high solar altitudes and the higher value for low solar altitudes and night time.

The PET index was calculated on the basis of simulated hourly values for air temperature and MRT, whereas measured values of vapour pressure and wind speed were used. The wind speeds were constant throughout the day but decreased with increasing H/W ratio. Similarly, measured values of vapour pressure were used. For the Colombo calculations, the average vapour pressure of the measurement period was used. Since no clear connection between H/W ratio and vapour pressure had been found, the same value was used for all canyons (Emmanuel and Johansson 2006). For the Fez case,

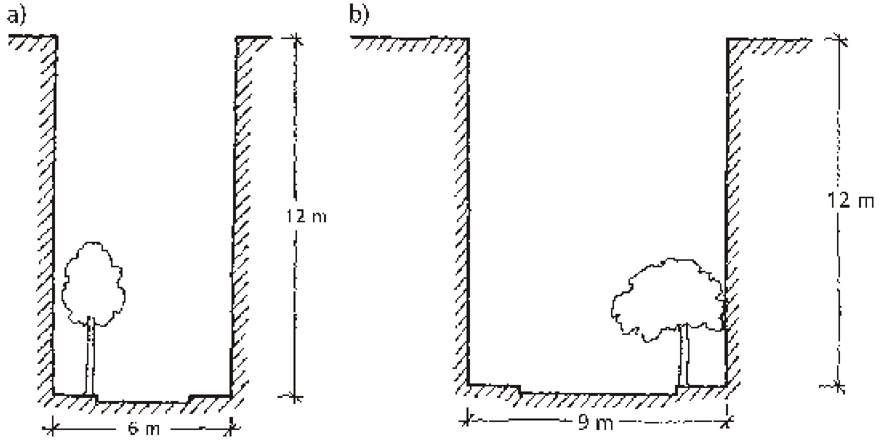


Fig. 5 The simulation cases for shading trees: (a) Fez, (b) Colombo.

the vapour pressure decreased slightly with increasing H/W ratio in accordance with the measurements (Johansson 2006). For both cases, the vapour pressure was assumed to be constant throughout the day. The wind and humidity input data for the PET calculations are shown in Table 2.

Unfortunately, the thermal comfort zone for PET in hot dry and hot humid climates has not been defined. In this study, the upper discomfort limit proposed by Ahmed (2003) for the summer in Dhaka, Bangladesh, which roughly corresponds to PET = 33°C (see Johansson and Emmanuel 2006), has been included as a reference for Colombo and the summer in Fez. The lower discomfort limit suggested for temperate climates – PET = 18°C (Matzarakis et al. 1999) – has been included as a reference for the winter in Fez. It should be noted, however, that this limit concerns a seated individual wearing typical indoor clothing.

The detailed output of the ENVI-met model, which gives the spatial variation of the air temperature and MRT, made it possible to calculate how the PET index varied within the canyon.

3 Results

All results presented here only consider only daytime conditions.

Parametric study of Fez

Effect of H/W ratio and orientation

The relationships between the maximum daytime air temperature (defined as the temperature at 14:00 h) and the H/W ratio for both the summer and winter in Fez are shown in Fig. 6. For both seasons, the trend is for air temperature to decrease with increasing H/W ratio. In summer, daytime air temperature was found to peak for H/W ratios of about 1, see Fig. 6a. A sharp decrease in air temperature was found for H/W ratios of ≥ 2 in summer and for H/W ratios of ≥ 1 in winter.

In the summer case, the daytime temperature was found to be lower in canyons with a north-south orientation. This is because east-west oriented streets receive solar radiation during a longer period of the day. In the winter case, the east-west streets showed lower air temperatures than the north-south streets, although the difference was only about 1°C. For both seasons, the impact of street orientation is negligible for H/W ratios of ≥ 2.

Daytime PET values, calculated as average PET at pedestrian level (at 1.5 m height), for the Fez canyons are shown in Fig. 7 (summer) and Fig. 8 (winter). The assumed upper and lower comfort limits (see Section 5.1) are included for reference. During both seasons, and for both east-west and north-south oriented streets, the trend is for PET values and the duration of high PET values to decrease with increasing H/W ratios. However, for the same H/W ratio, north-south oriented streets are more comfortable than east-west oriented streets, during both summer and winter. The difference is most pronounced for H/W ratios of below about 4 since for higher H/W ratios the amount of solar radiation that reaches the street is small, regardless of orientation.

The peaks at 09:00 h and 15:00 h in the east-west canyon in summer are due to the fact that the sun is positioned due-east and due-west respectively at these times and, consequently, the entire canyon is exposed to solar radiation.

It should be noted that Figs. 6.12 and 6.13 show average values for the whole canyon width. In east-west oriented streets, for example, PET values on the northern side of the street will reach magnitudes above 20°C during hours of solar exposure in the winter (see, e.g. Fig. 15).

Effect of surface reflectivity

Surface reflectivity proved to have a minor effect on PET at street level. The difference in maximum PET between the cases with the

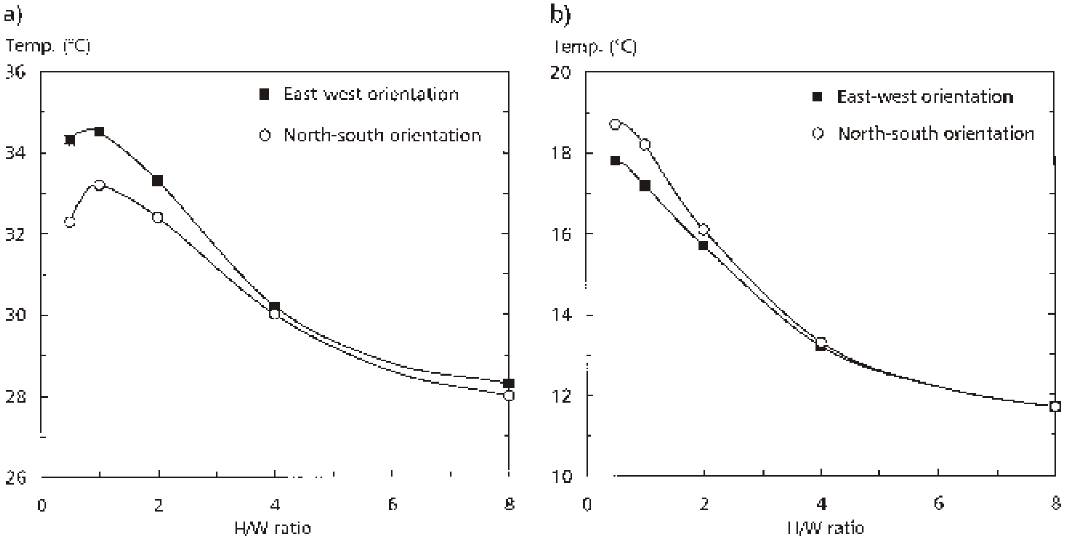


Fig. 6 Maximum daytime air temperature (at 14:00 h) as a function of H/W ratio in Fez for (a) the summer (15 July) and (b) the winter (15 January).

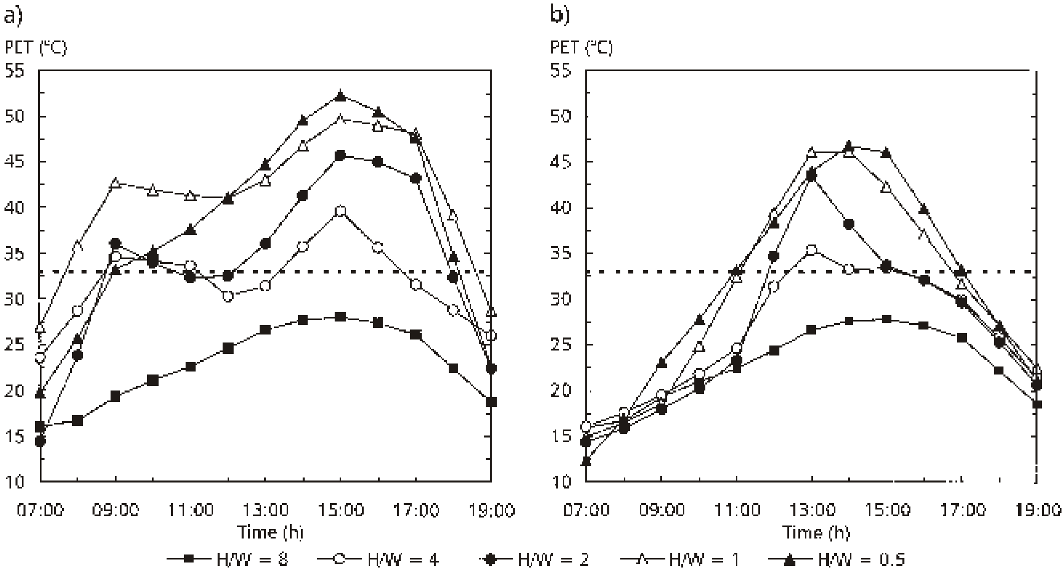


Fig. 7 *PET at pedestrian level (average for the entire canyon width at 1.5 m height) for the different H/W ratios for the summer in Fez (15 July). (a) East-west oriented streets and (b) north-south oriented streets. The assumed upper comfort limit (dashed line) is included as a reference.*

highest and lowest reflectivity was 5°C in summer (Fig. 9a) and 2°C in winter. However, what was unexpected was that the MRT (and consequently PET) *increases* with increasing reflectivity. This suggests that, in these simulations, the effect on MRT of increased reflection was greater than the effect of lower surface temperatures. This may be due to the fact that ENVI-met 3.0 does not take the thermal mass of the façades into account by. That is to say, the façades are unable to store the absorbed solar radiation. This has the effect

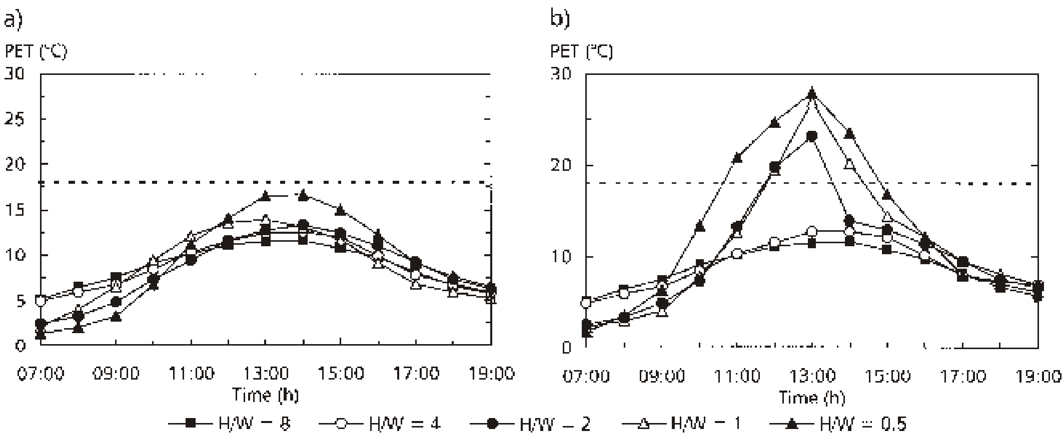


Fig. 8 *PET at pedestrian level (average for the entire canyon width at 1.5 m height) for the different H/W ratios for the winter in Fez (15 January). (a) East-west oriented streets and (b) north-south oriented streets. The assumed lower comfort limit (dashed line) is included as a reference.*

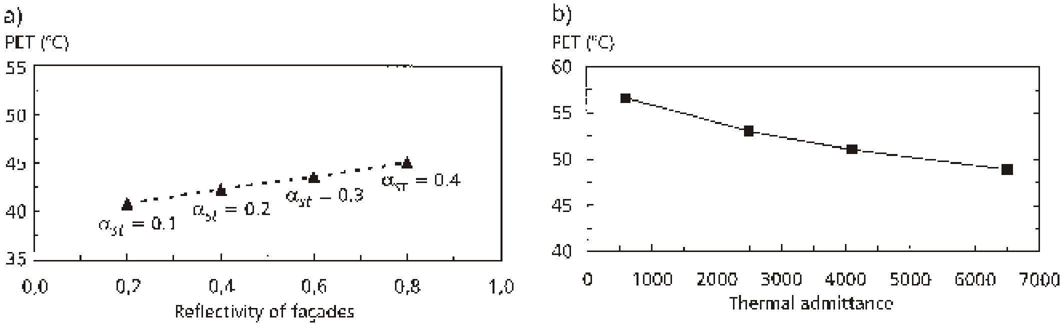


Fig. 9 The daytime PET at 14:00 h for the summer in Fez as a function of (a) surface reflectivity of street and façades (α_{st} = reflectivity of the street) and (b) thermal admittance μ. It should be noted that μ of the façades have been added to m of the street (see Fig. 2, eq. 4 and Table 2).

that afternoon temperatures will be underestimated, particularly for dark surfaces.

Effect of thermal mass

PET tended to decrease with increasing thermal admittance m of the street surface. This was expected, since the increased heat penetration into the substrate will lead to lower surface temperatures in the daytime (and consequently lower MRTs), as well as less sensible heat. However, the effect was greater for the summer case than for the winter case. In summer, the difference in maximum PET between the lowest and highest m was about 8°C (Fig. 9b). In the winter, the difference was only 2°C. This is because less solar radiation reaches the street level in the winter.

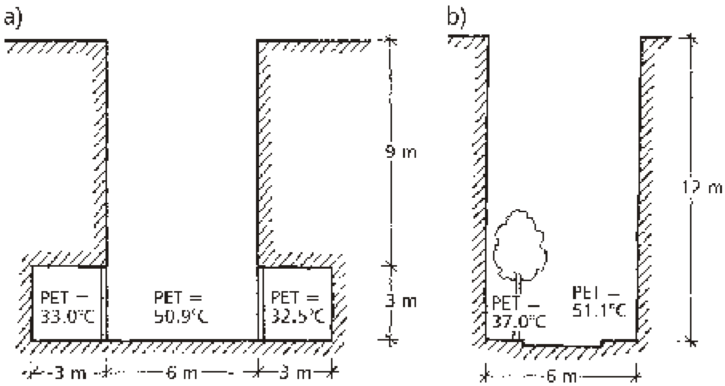


Fig. 10 Effect of shade on maximum PET (at 15:00 h) for the summer in Fez (15 July): (a) east-west street with colonnades on both sides, (b) east-west street with a row of trees on the northern side.

Effect of shading at street level

The effect of shading by colonnades and a row of trees on maximum PET for the summer is shown in Fig. 10. It is clear that overhead shading significantly improves thermal comfort conditions. Beneath the colonnade, PET is about 18°C lower than in the centre of the canyon and just below to the assumed discomfort threshold (Fig. 10a). The row of trees is a little less efficient than a colonnade since the tree canopies have some transparency. Beneath the trees, PET is about 14°C lower than in the centre of the canyon, but clearly above the assumed discomfort limit (Fig. 10b).

Parametric study of Colombo

Effect of H/W ratio and orientation

Contrary to the case of Fez, and contrary to measurement results, the simulated air temperatures varied only marginally between the Colombo cases. The simulated differences in maximum daytime temperatures between the different H/W ratios and street orientations were less than 0.5°C. This is probably due to the turbulence model used by ENVI-met, which differed from that used in the Fez simulations, see the Calibration section above.

Daytime PET (average value at a height of 1.5 m) for the Colombo canyons on a clear day is shown in Fig. 11. The assumed upper comfort limit (see Section 5.1) is included as a reference. As with the Fez summer case, the trend is for both PET values and the duration of uncomfortably high PET values to decrease with increasing H/W ratio. For very low H/W ratios (below 0.6), the influence of street orientation is marginal, but as the H/W ratio decreases, north-south oriented streets are more comfortable than east-west oriented streets. The former have lower maximum values and the duration of uncomfortable PET values is shorter than for the latter. To achieve a noticeable improvement in outdoor thermal comfort, east-west streets would need to be very deep, at least H/W = 4. For north-south oriented streets, a noticeable effect is seen for H/W ratios as low as about 2.

Effect of surface reflectivity

Surface reflectivity proved to have a minor effect on simulated maximum daytime PET at street level. As in the case of Fez, there is an

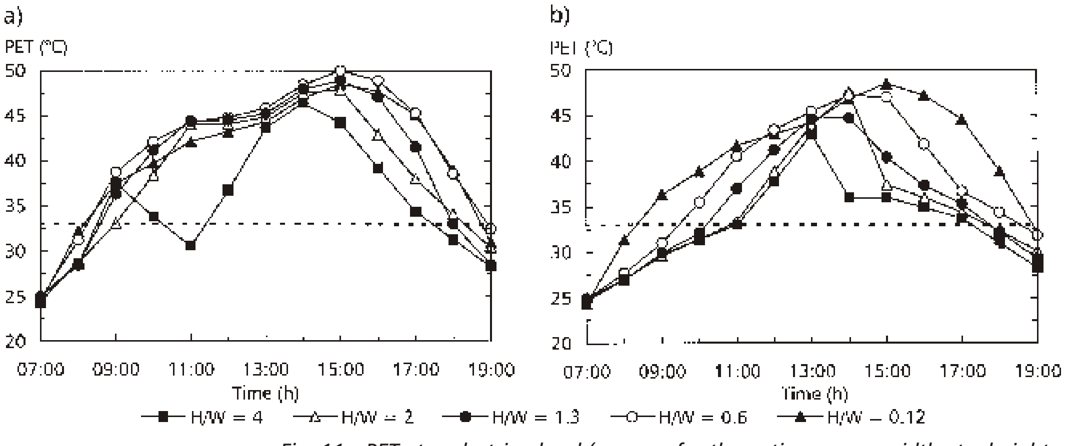


Fig. 11 PET at pedestrian level (average for the entire canyon width at a height of 1.5 m) for different H/W ratios on a clear day in Colombo (3 May). (a) East-west oriented streets and (b) north-south oriented streets. The assumed upper comfort limit (dashed line) is included as a reference.

unexpected tendency for PET values to increase with increasing reflectivity (see the comment on the Fez results above). For the Colombo case, the difference in PET between the darkest and lightest alternative was 2°C (Fig. 12a).

Effect of thermal mass

As in the case of Fez, PET tended to decrease with increasing thermal admittance μ of the street. However, the difference in maximum daytime PET was only 5°C between the lowest and highest μ value (Fig. 12b).

Effect of shading at street level

The effect of shading by colonnades and rows of shading trees on maximum PET is shown in Fig. 13. Maximum PET was about 10°C lower under the colonnades than in the centre of the canyon. Nonetheless, the simulated values are still higher than the assumed discomfort threshold. The trees are a little less efficient than a colonnade, since tree canopies provide some transparency and their ability to reduce PET was limited to about 7°C.

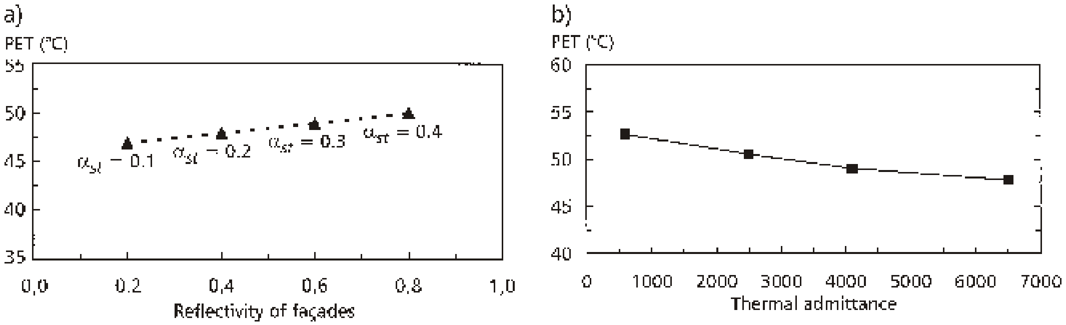


Fig. 12 The daytime PET at 14:00 h for Colombo as a function of (a) surface reflectivity of street and façades (α_{st} = reflectivity of the street) and (b) thermal admittance μ. It should be noted that μ of the façades have been added to μ of the street (see Fig. 2, eq. 4 and Table 2).

Effect of detached blocks on wind speed

Although simulated wind speeds were unrealistically low, the opening up spaces perpendicular to the street canyon of the base case clearly led to increased wind speeds at pedestrian level. The simulated wind speed in the street increased from 0.04 to 0.093 m/s. However, in the intersections, the wind speed reached 0.19 m/s.

Optimised street design

The results of the parametric study showed that the H/W ratio, street orientation and provision of horizontal shading had the greatest influence on thermal comfort at street level. It was also shown that heavy building materials are favourable in a warm climate, whereas the influence of material properties proved to be negligible during the cold season in Fez. Since the ground surface and building materials most commonly used in both Fez and Colombo, such as asphalt, concrete, burnt clay bricks, concrete blocks and plaster, are already of

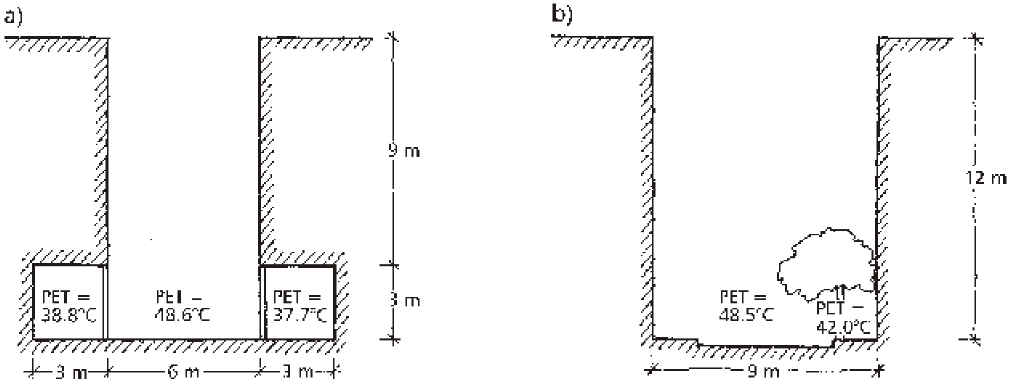


Fig. 13 Effect of shade on maximum PET (at 15:00 h) in Colombo (3 May). (a) East-west canyon with colonnades on both sides, (b) east-west street with one row of trees on the northern side.

medium to high density, the thermal admittance values used in the base cases were kept. Similarly, the reflectivity values of façades and the ground were not changed, since these proved to have an insignificant impact on thermal comfort in the simulations.

Optimised design for Fez

The fact that Fez has one warm and one cold season makes it difficult to optimise the design. What is a design advantage in the summer is normally a disadvantage in the winter. One way to overcome this problem is to combine streets that are comfortable in the summer with streets that show favourable winter characteristics.

The results from the parametric study showed that a street with favourable summer characteristics should have a high H/W ratio. However, the appropriate H/W ratio will depend on street orientation. North-south oriented streets should preferably have H/W ≥ 2. East-west streets, on the other hand, need to be deeper (H/W ≥ 4), to provide adequate shade in the summer. For lower H/W ratios than those suggested above, streets should be provided with some type of horizontal shading such as projecting first floors, colonnades, shading trees or other devices to provide shade around midday in summer.

To achieve comfortable conditions in winter, east-west streets should have a H/W ratio sufficiently low to allow direct solar radiation to reach pedestrian level. If the H/W ratio is less than 0.7 and there is a colonnade on the northern side, solar access can be provided on that side of the street for a large part of the day during the winter months. Moreover, the colonnade will provide shade in summer. However, such streets should also preferably have some form of overhead shading, such as trees, on the southern side to improve the shade in summer. North-south oriented streets require a H/W ratio of ≤ 2 to provide some comfort in winter.

The various design considerations were combined to form "best cases", presented as the street designs shown in Fig. 14 (summer) and Fig. 15 (winter). The daytime variation in PET for these canyons is also shown in the figures. North-south streets with H/W = 2 have been selected for both seasons since they constitute a compromise

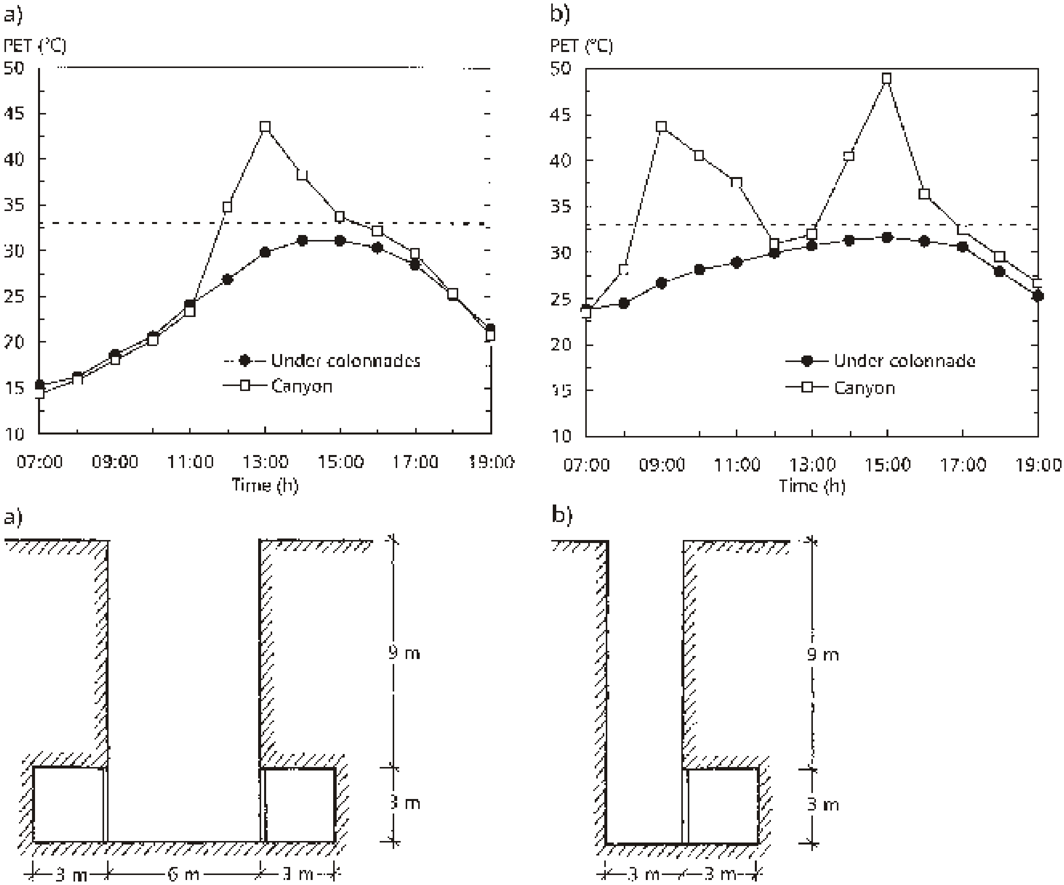


Fig. 14 Optimum design of street canyons for the summer in Fez. (a) North-south street of H/W = 2 with colonnades on both sides, (b) east-west street of H/W = 4 with a colonnade on the northern side. The graphs show the daytime PET variation for 15 July and include the assumed upper comfort limit (dashed line).

between summer and winter comfort. Colonnades have been added on both sides of the street to provide necessary shade in summer during times of solar exposure. In winter, the north-south canyon of H/W = 2 reached “comfortable” levels around noon. The shallower east-west canyon of H/W = 0.67, which has a colonnade on the northern side, can provide “comfortable” conditions for a larger part of the day (between about 11:00 h and 15:00 h). This period will be slightly shorter in December but longer in February.

Optimised design for Colombo

As in the case of Fez, the parametric study showed that streets should have high H/W ratios to improve thermal comfort conditions. However, to achieve improved comfort conditions for street canyons oriented east-west, the most problematic orientation, H/W ratios would have to be as high as 4. North-south oriented streets should have H/W ratios of at least 2. Regardless of H/W ratio and orientation, streets in Colombo require horizontal shading – through pro-

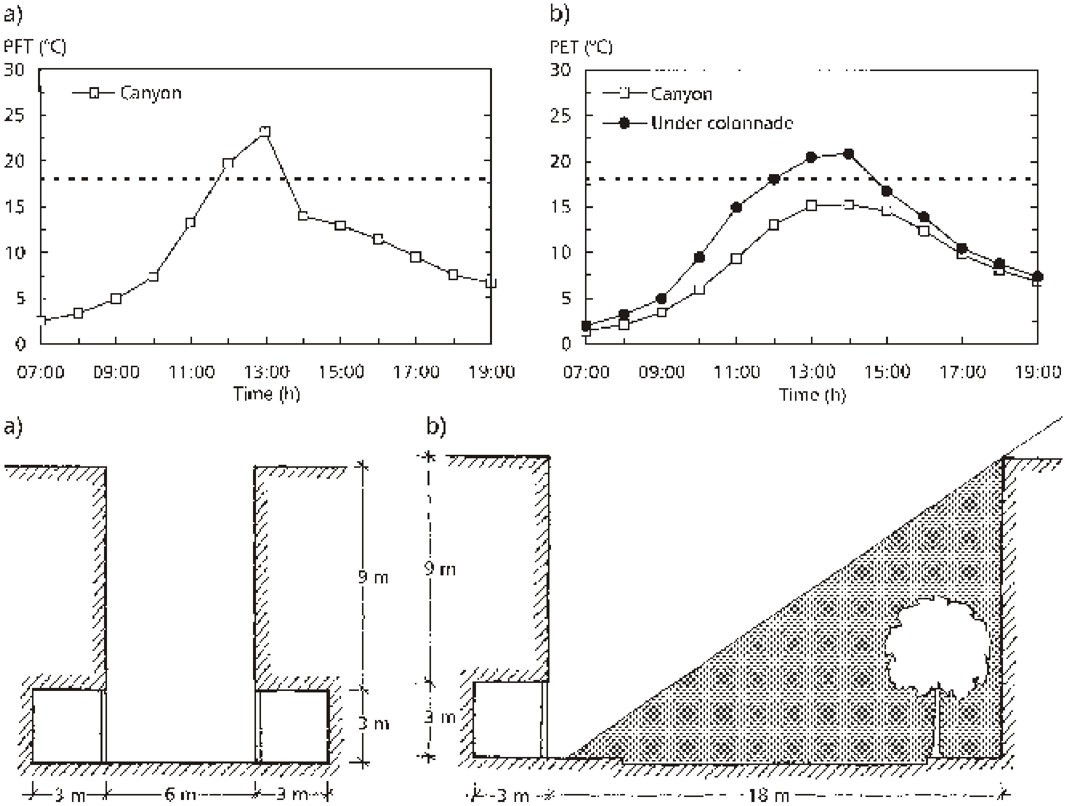


Fig. 15 Optimum design of street canyons for the winter in Fez. (a) North-south street of H/W = 2 with colonnades on both sides, (b) east-west street of H/W = 0.67 with a colonnade on the northern side and a row of shading trees on the southern side. The graphs show the daytime PET variation for 15 January and include the assumed lower comfort limit (dashed line).

jecting first floors, colonnades, shading trees or other horizontal shading devices – to improve comfortable conditions between about 11:00 h and 16:00 h.

In Colombo, it is also important to facilitate air flow. Consequently, long, uninterrupted street frontages are disadvantageous, since they block the wind. One way of providing shade and air movement is to use detached, rather high blocks, which would provide shade at street level and allow the wind to be channelled between the buildings. Buildings could also be varied in height and raised on columns to increase air movement at pedestrian level. Since the sea-breeze in Colombo comes from the west, a good strategy would be to allow fairly wide east-west oriented streets near the coast to maximise the penetration of the sea breeze.

Examples of optimum design for street canyons are shown in Fig. 16 (north-south orientation) and Fig. 17 (east-west orientation), including daytime PET variation for these canyons. It can be seen that a north-west oriented street with H/W = 2 and colonnades causes only slight discomfort during the hottest hours (12:00 h – 16:00 h). The case is very similar for the east-west oriented street of H/W = 4.

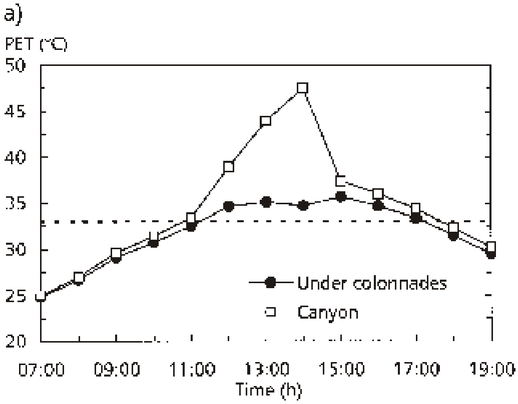
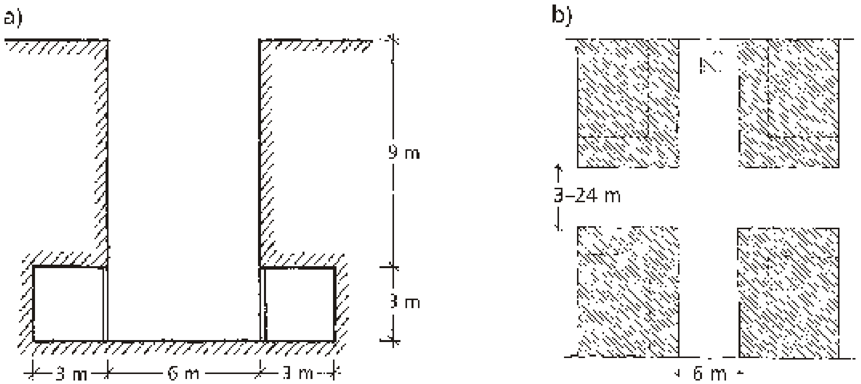


Fig. 16
Optimum design for a north-south oriented street canyon in Colombo. (a) Section of H/W = 2 with colonnades on both sides. The graph shows the daytime PET variation for 3 May and include the assumed upper comfort limit (dashed line). (b) Plan showing detached blocks allowing the westerly sea breeze to enter the street.



The shallow east-west canyon (Fig. 17b) is assumed to be near the coast and therefore the wind speed was increased by 100% compared to the base case. Still the canyon is extremely uncomfortable. However, under the colonnades the comfort is much better, although it is above the assumed discomfort level between 12:00 h and 17:00 h.

4 Discussion

Effect of H/W ratio and orientation

For the case of Fez, the H/W ratio proved to have the biggest influence on the air temperature. The effect tended to be especially big for canyons of H/W ratios of around 2 and above in summer and for H/W = 1 and above in winter. The effect of orientation on air temperatures was fairly small, but the fact that the north-south oriented street was up to 2°C cooler than the east-west oriented street in the summer agrees well with the findings of Ali-Toudert and Mayer (2006). However, in reality the difference in air temperature will be less because of street intersections and mixing of air between streets of different orientation.

For the case of Colombo, the negligible differences in air temperature between canyons of different H/W ratios, which are contradictory to field measurements (Emmanuel and Johansson 2006), are likely to be linked to turbulence model of the simulation programme, see the section on Calibration above.

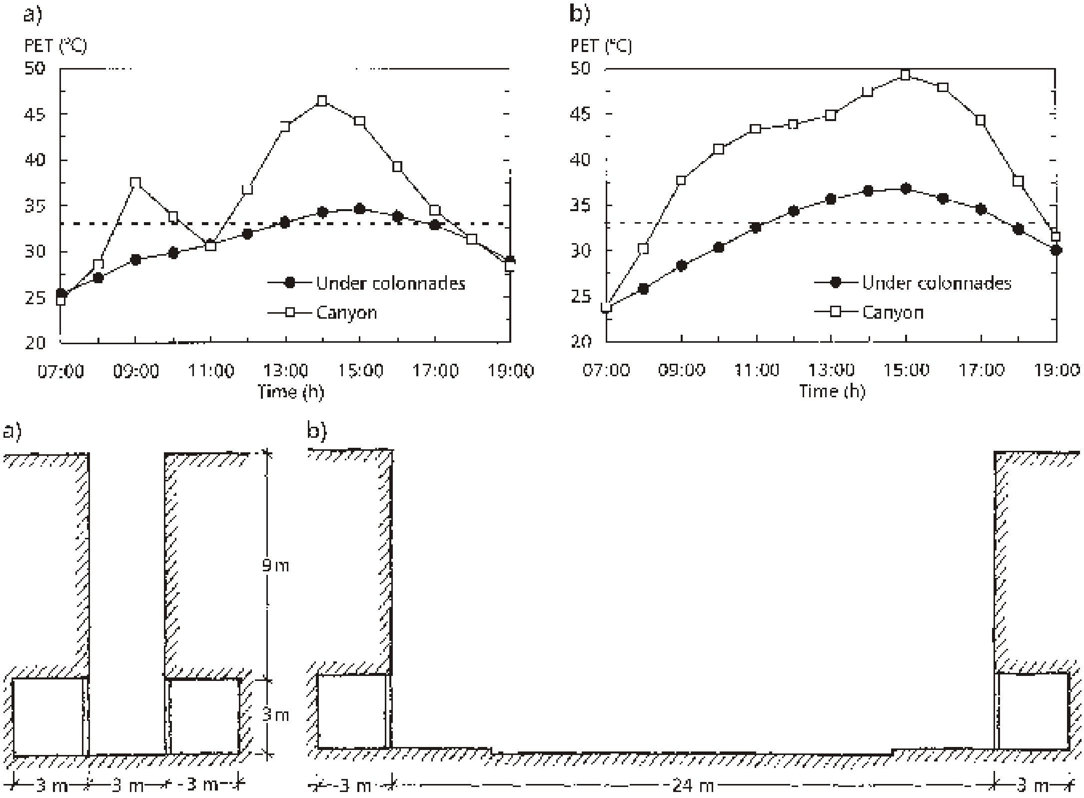


Fig. 17 Optimum design of east-west oriented street canyons in Colombo.
(a) Section of H/W = 4 with colonnades on one side.
(b) A shallower canyon of H/W = 0.5, with colonnades on both sides, designed to allow the westerly sea breeze to penetrate the city.
The graphs show the daytime PET variation for 3 May and include the assumed upper comfort limit (dashed line).

The parameter that was most affected by the H/W ratio was MRT at pedestrian level. The canyon geometry influences both the exposure to solar radiation and pedestrians' radiative heat exchange, as well as surface temperatures. Both for Fez and Colombo, the simulations showed that PET tends to decrease with increasing H/W ratio. The decrease concerns both the maximum value and the duration with high values, and existed both for the summer and winter cases. The summer results for Fez agree well with the findings of Ali-Toudert and Mayer (2006) in a similar climate.

Also the street orientation has a great impact on MRT, which is reflected in the PET index. The simulated effect of street orientation on PET was significant, showing that both maximum PET and the duration of uncomfortably high PET values are lower for north-south oriented streets. For such streets, shade is provided by the buildings both in the morning and the afternoon provided the H/W ratio is sufficiently high. East–west oriented streets are far more problematic.

The fact that north-south oriented streets give lower PET than east-west oriented streets of the same H/W ratio agrees well with the findings of Ali-Toudert and Mayer (2006). Similarly, Pearlmutter et al. (2005) found the radiative heat gain of a body in the centre of the canyon to be lower in north-south streets than in east-west streets. The difference in PET is most pronounced for H/W ratios of less than about 4, since for higher H/W ratios, the amount of solar radiation reaching the street is small, regardless of orientation.

Effect of surface reflectivity and thermal mass

For both cities, the simulated effect of surface reflectivity is limited and the results are contrary to the common belief that light colours are preferable from a thermal comfort point of view since they give lower surface temperatures. Here, the opposite was found: the MRT (and hence PET) increased with increasing surface reflectivities. The reason is probably that the increase in reflected solar radiation is bigger than the decrease in long-wave radiation from the surfaces when the reflectivity increases.

For both cities, the simulated effect of thermal mass of the street proved to be surprisingly small. A probable reason is that since the building façades have no thermal mass in ENVI-met, the amount of solar radiation that is stored in surfaces is limited to the street. This explains why the impact was especially small for the winter case of Fez when solar altitudes are small and a greater part of the solar radiation strikes vertical elements.

Thus, the effect of both the surface reflectivity and thermal properties of surface materials might have been more significant if a simulation programme had been used that took the thermal mass of buildings into account. However, no such programme, which also is user-friendly, is currently available.

Effect of shading by colonnades and trees

For Fez, the simulations showed that shading by colonnades and trees was very efficient in lowering PET. This trend agrees well with the findings of Ali-Toudert and Mayer (2006) in hot dry Beni-Isguen. Similarly, for Colombo the simulations show that shade from either colonnades or trees gives considerably lower PET values, resulting in comfortable or only slightly uncomfortable conditions according to the assumed comfort limits. These findings agree with Ahmed (2003), who found that well shaded urban spaces often were considered comfortable in the hot humid summer climate of Dhaka, Bangladesh. In general, colonnades provide more efficient shading than trees, since the latter have a certain degree of transparency.

However, shading is especially efficient in the summer climate of Fez, since solar radiation is dominated by the direct component. The PET values in shade are higher in Colombo although global radiation in Colombo is lower (see Fig. 1). This is due to the higher amount of diffuse radiation in Colombo.

Microclimate simulations

The microclimate simulation tool used in this study, ENVI-met, proved to be a very useful tool to simulate the urban microclimate, especially as it provides detailed output on temporal and spatial variations of the microclimate. However, the fact that thermal mass of buildings is not considered is a serious shortcoming, which may give misleading results, especially for high building densities where buildings dominate. According to Grimmond and Oke (2002), the heat storage for dense built-up urban areas can be as high as 50% of the net radiation. Moreover, the present version of the programme also has some other limitations concerning the modelling of the buildings: all buildings have the same values of reflectivity and U-values, the indoor temperature is constant and there is no possibility to add shading divices.

The programme proved to underestimate diurnal temperature variations, a fact that has also been pointed out in other studies, e.g. Jansson (2006). In this study, the wind speeds were found to be unrealistically low. This might be due to the rather low grid size resolution was used compared to more detailed CFD studies, see e.g Tablada de la Torre (2006).

5 Conclusions

It may not be possible to achieve thermal comfort in urban environments in extreme climates such as those of Fez and Colombo throughout the day. However, with a good urban design the worst conditions may be mitigated and the time period of thermal comfort may be extended.

Simulations using ENVI-met 3.0 showed that high H/W ratios are in general favourable from a thermal comfort point of view for both cities. However, around noon, approximately 10:00–14:00 h, shade cannot be provided by the buildings alone. The simulations show that the use of colonnades and shading trees significantly lowers the MRT and hence give considerably lower PET values during these hours.

For the case of Fez, the results of this study suggested that H/W ratios for east-west streets should be as high as 4 to provide comfort in the summer. For north-south streets a H/W ratio of about 2 provided acceptable conditions both in summer and winter. To provide thermal comfort also in winter, at least some streets, preferably oriented east-west, should be wider to allow for solar access. The canyon of H/W = 0.67 with a colonnade on its northern side and trees planted along the southern side provided sufficient solar access under the colonnade in winter, while providing sufficient shade under the same colonnade and under the shading trees on the southern side in summer.

For the case of Colombo, the results of this study suggest that H/W ratios for east-west streets should be as high as 4 to provide comfort in the summer. For north-south streets a H/W ratio of about 2 provides acceptable conditions. In Colombo, spacing between buildings is preferable to permit air flow. This is especially important for the coastal strip to allow the westerly sea breeze to penetrate the city. Consequently, some east-west oriented streets in coastal areas should have H/W ratios as low as about 0.5.

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